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Combustion Modification Tests on a Subscale Cement Kiln for NOx Reduction

KVB, Inc., Irvine, CA

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COMBUSTION MODIFICATION TESTS ON A SUBSCALE CEMENT KILN FOR NO_x REDUCTION

by

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a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Natural Gas	Pollution Control	13B
Kilns	Flue Gases	Stationary Sources	13A
Cements		Cement Kilns	11B,13C
Nitrogen Oxides			07B
Combustion Control			21B
Coal			21D

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ABSTRACT

Field tests were conducted on a subscale rotary cement kiln to evaluate the effect of various combustion modifications on gaseous emissions. The test program was conducted with a research kiln donated by a cement company. The test unit was 8.2 m (27 feet) long and 0.38 m (15 inches) inside diameter and will produce 68 kg (150 lb) of clinker per hour. A coal burner was designed and built for the test program and the kiln was reworked to incorporate heated secondary air and flue gas recirculation. The effect on NO emissions of flue gas recirculation, diluted primary air, primary/secondary air ratio, burner tip velocity, and secondary air temperature were evaluated. The most effective combustion modification for coal firing was determined to be dilution of primary air with inert gas which resulted in a NO reduction of nearly 40 percent when the primary air oxygen concentration was reduced to 12 percent.

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Acknowledgment is also made of the contributions of the engineering and supervisory personnel of the cement plant at which the subscale kiln was located. Without their considerable effort and expense, the program could not have been conducted.

Limitations on Application of Data Reported

The pollutant emission data cited in this report pertain to a specific kiln; i.e., a subscale dry process rotary kiln. These data should not be used to estimate mean emissions from other kilns or to predict emission reduction potentials of combustion modifications until the modifications have been evaluated on other kilns.

SECTION 1.0

SUMMARY

1.1 OBJECTIVE

The overall objective of the contract, under which the work reported herein was conducted, was to investigate advanced combustion modification concepts requiring relatively minor hardware modifications that could be used by operators and/or manufacturers of industrial process equipment to reduce oxides of nitrogen emissions. Another objective was to investigate the feasibility of these modifications to the extent that they could be readily adopted by equipment manufacturers and operators.

The specific objective of the test program reported herein was to evaluate flue gas recirculation, vitiated primary air, primary/secondary air ratio, temperature of combustion air and coal carrier air velocity as they affect emission of nitrogen oxides in a subscale rotary cement kiln provided by a major cement manufacturer. The test results were to be compared with previous laboratory-scale tests and recommendations formulated for tests at a larger scale.

1.2 PAST WORK

The present program is a follow-on study intended to build upon the results of the program reported in Reference 1 conducted in a laboratory combustion tunnel. The objective of the earlier effort was to determine the effect of burner parameters on near-flame NO levels for both natural gas and coal fuels. This laboratory effort determined that combustion air preheat, fuel injection velocity, and oxygen content of the primary combustion air stream have first-order effects on NO levels. These parameters were then selected for implementation on the subscale kiln.

1.3 PRESENT TEST PROGRAM APPROACH

A detailed summary of test results and a discussion of those results are presented in Section 3.0. A brief review of the program approach is presented here.

During the previous program, several subscale test facilities were visited and evaluated. A test program was presented to the operators of these facilities and estimates of test costs were received from each. The selected subscale kiln offered the most operational flexibility and opportunity for the maximum data at minimum cost.

A coal burner and feed system were built and installed at the test site and the kiln was modified to incorporate combustion air preheat and flue gas recirculation. The initial test series was conducted firing natural gas to define kiln operation over a range of operating variables such as excess air, primary to secondary air ratio, and combustion air preheat.

Once the performance of the kiln was documented with natural gas fuel, a change to coal firing was implemented. Kiln NO emissions were evaluated as a function of combustion air temperature, primary air velocity, primary to secondary air ratio, tertiary air injection flue gas recirculation rate, and primary air oxygen content.

A summary of the significant results obtained from the test program is presented in Tables 1-1 and 1-2 for natural gas and coal firing, respectively.

1.4 CONCLUSIONS

The following conclusions were drawn from the testing and the analyses performed on the data:

- The subscale kiln tests corroborated previous laboratory combustion tunnel test results.
- NO emissions are very sensitive to excess O_2 level.

TABLE 1-1. SUMMARY OF TEST RESULTS: GAS FIRING - SUBSCALE CEMENT KILN[a]

Test Series		SA Temp °F	SA Temp K	% Primary Air	% FGR	Fuel Firing Rate MW	Fuel Firing Rate (10^6 Btu/hr)	Kiln Exit O_2 (%, dry)	NO (ppmv, @ 3% O_2, dry)	CO_2 (%, dry)	Maximum % NO Reduction from Baseline
PA/SA[b] Variation (20/80)	Baseline	1100	867	19.1	0	0.21	(0.70)	2.0	640	11.2	
		900	756	↓			↓	↓	600	↓	
		600	589						400		64.4
		300	422						243		
		Amb.		↓			↓	↓	228	↓	
PA/SA Variation (33/67)	Baseline	1200	922	33.0	0	0.21	(0.70)	2.0	300	11.5	
		600	589	↓			↓	↓	194	↓	
		300	422						180		43.3
		Amb.		↓			↓	↓	170	↓	
SA[c] Temp. Variation	Baseline	1000	811	14.6	0	0.19	(0.64)	2.0	404	14.2	
		900	756	↓			↓	↓	419	↓	
		800	700						364		47.5
		700	644						350		
		Amb.		↓			↓	↓	212	↓	
FGR[d]	Baseline	1168	904	28.0	0	0.19	(0.64)	2.0	340	15.8	
		↓		↓	21.6		↓	↓	163	↓	
					28.6				135		70.6
					32.6				110		
		↓		↓	33.8		↓	↓	100	↓	

[a] All CO data for the nominal O_2's listed are less than 200 ppmv.

[b] PA: Primary Air

[c] SA: Secondary Air

[d] FGR: Flue Gas Recirculation

TABLE 1-2. SUMMARY OF TEST RESULTS: COAL FIRING - SUBSCALE CEMENT KILN

Date	SA Temp. °F	SA Temp. (K)	PA Velocity fpm	PA Velocity (m/s)	% PA	Avg. O_2 (%)	Avg. CO (ppm)	Avg. NO (ppm corrected to 3% O_2, dry)	CO_2 (%)	Comments	
7/27/82	1099	(866)	3338	(17)	28.4	3.5	25	753	16.4	Evaluate the effect of SA temperature on NO emissions; PA = constant O_2 = constant.	
7/27/82	1003	(816)	3338	(17)	27.9	3.7	35	794	15.4		
8/04/84	1145	(892)	3338	(17)	29.4	3.8	559	826	14.6		
7/29/82	1167	(904)	3232	(16.4)	25.8	3.6	125	848	15.4		
8/12/82	1162	(901)	2950	(15)	21.0	3.7	148	806	15.5	Velocity variation; varied primary air flow.	
8/12/82	1158	(899)	2504	(12.7)	19.3	3.6	396	643	17.8	Secondary air ΔP was relatively constant.	
8/12/82	1166	(903)	2285	(11.6)	17.1	4.1	303	708	15.3		
8/12/82	1169	(905)	2128	(10.8)	16.2	5.3	963	773	15.5		
8/12/82	1161	(900)	2504	(12.7)	9.3	4.3	293	711	17.6	PA/SA variation tests. Varied PA flow and SA flow at constant O_2.	
8/11/82	1187	(915)	2915	(14.8)	22.2	3.6	608	775	15.1		
7/29/82	1167	(904)	3232	(16.4)	25.4	3.6	136	822	15.8		
8/04/82	1153	(896)	3268	(16.6)	29.8	4.1	268	848	14.6		
8/04/82	1130	(883)	3440	(17.5)	30.1	5.4	452	847	13.8	Baseline for series to evaluate FGR, 0% FGR	
8/04/82	1144	(891)	3390	(17.2)	29.7	5.0	79	836	16.4	19% FGR	
8/04/82	1160	(900)	3440	(17.5)	30.1	5.6	167	788	13.7	21% FGR	
8/10/82	1140	(889)	3120	(15.8)	22.5	2.9	481	727	15.3	Baseline for PA dilution tests	High PA Velocity
8/10/82	1160	(900)	2890	(21.7)	21.7	3.7	104	700	13.5	18% O_2 in PA	
8/10/82	1140	(889)	3120	(15.8)	22.5	2.3	550	613	16.2	12% O_2 in PA	
8/12/82	1160	(900)	2500	(12.7)	19.3	5.0	188	771	17.5	Baseline for PA dilution tests	Low PA Velocity
8/12/82	1160	(894)	2500	(12.7)	18.4	4.0	87	635	17.9	15% O_2 in PA	
8/12/82	1160	(900)	2500	(12.7)	19.7	3.8	440	544	17.6	12% O_2 in PA	

PA: Primary Air

SA: Secondary Air

FGR: Flue Gas Recirculation

- Flue gas recirculation is more effective with gas firing than with coal firing.

- Primary air dilution with inert gas was the most effective combustion modification for NO reduction firing coal.

- Primary air vitiation is recommended for further investigation on larger scale cement kilns.

SECTION 2.0

INSTRUMENTATION, PROCEDURES, AND FACILITIES

This section presents a description of the instrumentation used to measure the gaseous emissions, the test facilities used to conduct the combustion modification tests, and the operation procedures for the kiln.

2.1 EMISSION MEASUREMENT INSTRUMENTATION

The emission measurements were made with instrumentation mounted in the mobile laboratory pictured in Figure 2-1. All the instruments require sample conditioning equipment contained in this trailer owned by EPA-IERL/RTP and operated by KVB on EPA contracts. The gaseous species measurements are made with analyzers maintained in the mobile laboratory. Additional portable analyzers are carried to sample ports for spot measurements. Weighings and titrations for free lime analysis of clinker samples were conducted in the rear of the mobile laboratory. The trailer also includes work areas for meetings and day-to-day review of the test plan.

Figures 2-2 and 2-3 are interior views of the mobile laboratory. Figure 2-2 shows the console with gaseous analyzers, recorders, and computer for data recording. Figure 2-3 shows the work area in the rear of the laboratory. This work area includes a fume hood, refrigerated storage and oven.

The analytical system consists of five analyzers and associated equipment for simultaneously measuring the composition of the flue gas. The analyzers, recorders, valves, controls and manifolding are mounted to a panel in the trailer. The analyzers are shock mounted to prevent vibration damage. The flue gas constituents measured by the analyzers are oxides of nitrogen (NO, NO_x), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and sulfur dioxide (SO_2). In addition, a gas chromatograph is installed for measuring hydrocarbons (HC).

Figure 2-1. KVB Mobile Emissions Measurement Laboratory

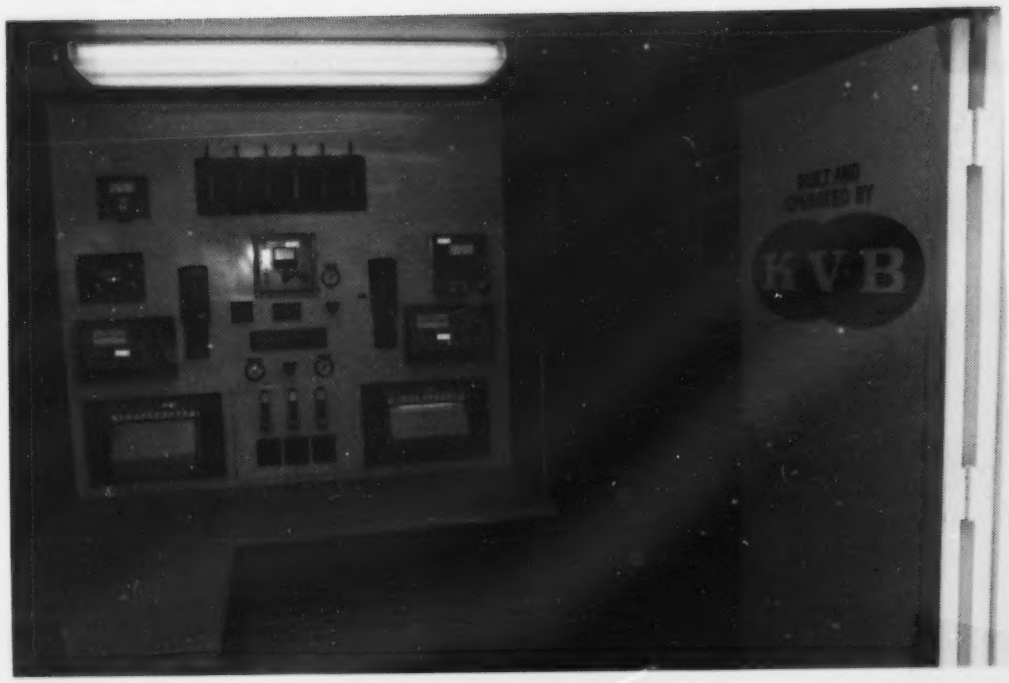


Figure 2-2. Interior View of Mobile Laboratory Showing Gaseous Analyzers and Strip Chart Recorders.

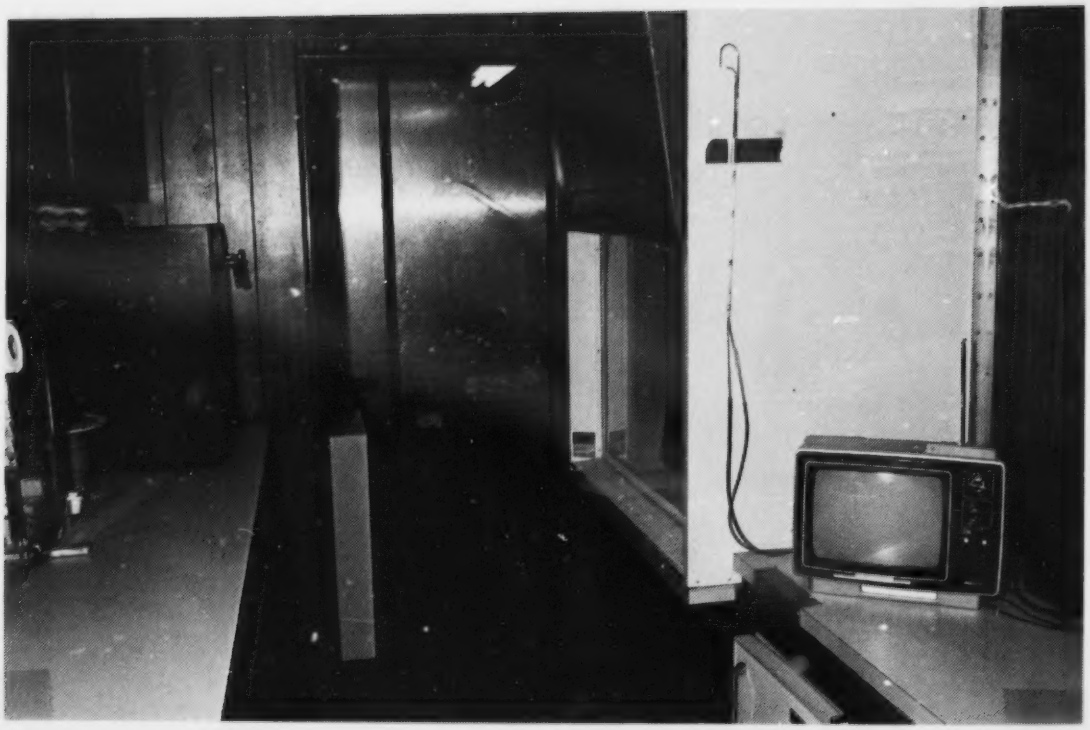


Figure 2-3. Interior View of Mobile Laboratory Showing Work Area.

For the gas and coal firing test series, only NO was measured. Measurement of total NO_x ($NO + NO_2$) requires a heated sample line and involves a differential measurement of NO and total NO_x, the difference being NO_2. Conditions in the subscale kiln were not sufficiently steady to allow accurate differential determination of NO_2. Thus, the added complexity of a heated line was not deemed necessary and NO_2 was not measured. All NO emissions are corrected to 3 percent O_2 and reported on a dry volume basis.

A portable Teledyne oxygen analyzer was used to monitor the volume percent oxygen in the primary, tertiary and recycle flue gas streams.

2.1.1 Gaseous Emissions Analyzers

Listed below are the gaseous species to be measured, the analyzer model and the range and accuracy of each analyzer. A detailed discussion of each follows:

- Nitric Oxide/Total Oxides of Nitrogen (NO/NO_x)
  Thermo Electron Model 10 Chemiluminescent Analyzer
  Range: 0-2.5, 10, 25, 100, 500, 1000, 2500, 10,000 ppm NO
  Accuracy: ± 1% of full scale

- Carbon Monoxide
  Beckman Model 365 NDIR Analyzer
  Range: 0-500 and 0-2000 ppm CO
  Accuracy: ± 1% of full scale

- Carbon Dioxide
  Beckman Model 864 NDIR Analyzer
  Range: 0-20, 0-50, and 0-100% CO_2
  Accuracy: ± 1% of full scale

- Oxygen
  Teledyne Model 326A Analyzer
  Range: 0-5, 10, and 25% O_2 full scale
  Accuracy: ± 2% of full scale

- Sulfur Dioxide
  Dupont Series 400 Photometric NDUV Analyzer
  Range: 0-100 and 0-5000 ppm

- Hydrocarbons
  Carle Instrument Gas Chromatograph
  Accuracy: ± 1% of full scale

The oxides of nitrogen monitoring instrument used is a Thermo Electron chemiluminescent nitric oxide analyzer. The operational basis of the instrument is the chemiluminescent reaction of NO and O_3 to form NO_2. Light emission results when electronically excited NO_2 molecules revert to their ground state. This resulting chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier, the output of which is linearly proportional to the NO concentration.

The basic analyzer is sensitive only to NO molecules. To measure NO_x (i.e., NO + NO_2), the NO_2 is first converted to NO. This is accomplished by a converter which is included with the analyzer. The conversion occurs as the gas passes through a thermally insulated, resistance heated, stainless steel coil. With the application of heat, NO_2 molecules in the sample gas are reduced to NO molecules, and the analyzer now reads NO_x. NO_2 is obtained by the difference in readings obtained with and without the converter in operation.

Specifications:

Accuracy: 1% of full scale
Span Stability: ± 1% of full scale in 24 hours
Zero Stability: ± 1 ppm in 24 hours
Power Requirements: 115 ± 10V, 60 Hz, 1000 watts
Response: 90% of full scale in 1 sec (NO_x mode), 0.7 sec NO mode
Output: 4-20 ma
Sensitivity: 0.5 ppm
Linearity: ± 1% of full scale
Vacuum Detector Operation
Range: 2.5, 10, 25, 100, 500, 1000, 2500, 10,000 ppm full scale

Carbon monoxide concentration is measured by a Beckman 365 nondispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO analyzer are 0 to 500 and 0 to 2000 ppm.

Specifications:

Span Stability: ± 1% of full scale in 24 hours
Zero Stability: ± 1% of full scale in 24 hours
Ambient Temperature Range: 32°F to 120°F
Line Voltage: 115 ± 15V rms
Response: 90% of full scale in 0.5 or 2.5 sec
Precision: ± 1% of full scale
Output: 4-20 ma

Carbon dioxide concentration is measured by a Beckman Model 864 short path-length, nondispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. A linearizer is supplied with the analyzer to provide a linear output over the range of interest. The operating ranges for the CO_2 analyzer are 0 to 20 percent, 0 to 50 percent, and 0 to 100 percent.

Specifications:

Span Stability: ± 1% of full scale in 24 hours
Zero Stability: ± 1% of full scale in 24 hours
Ambient Temperature Range: 32°F to 120°F
Line Voltage: 115 ± 15V rms
Response: 90% of full scale in 0.5 or 2.5 sec
Linearity: Linearizer board installed for one range
Precision: ± 1% of full scale
Output: 4-20 ma

A Teledyne Model 326A Oxygen analyzer is used to automatically and continuously determine the oxygen content of the flue gas sample. Oxygen in the flue gas diffuses through a Teflon membrane and is reduced on the surface of the cathode. A corresponding oxidation occurs at the anode internally and an electric current is produced that is proportional to the concentration of oxygen. This current is measured and conditioned by the instrument's electronic circuitry to give a final output in percent O_2 by volume for operating ranges of 0 to 5 percent, 0 to 10 percent, or 0 to 25 percent.

Sulfur dioxide (SO_2) concentration in the flue gas will be measured by the Dupont Series 400 photometric analyzer. This instrument uses nondispersive ultraviolet (NDUV) absorption to determine species concentration. Optical energy from a source lamp passes through the sample, then is split and passed through two optical filters onto two phototubes. One filter passes energy at a reference wavelength, the other at a measuring wavelength, where SO_2 absorbs energy. The differential between the two energy pulses is proportional to SO_2 concentration. The instrument has a lower detectable limit of 2 ppm, and measurement ranges from 0 to 200 ppm to 2000 ppm. Maximum sample temperature at the inlet is 538°C. To prevent water condensation and consequent loss of SO_2, the sample is provided to the instrument through the heated sample line system.

Specifications:

Noise: Less than 1/4%
Drift: Less than 1% full scale in 24 hours
Accuracy: (± 1% of analyzer reading) + (± 1/4% of full scale range)
Sample cell: 304 stainless steel, quartz windows
Flow rate: 6 CFH
Light source: Either mercury vapor, tungsten, or "OSRAM" discharge type lamps
Power rating: 500 watts maximum, 115V, 60 Hz
Reproducibility: 1/4% of scale
Electronic response: 90% in 1 sec
Sample temperature: 378 K (220°F)
Output: 4-20 ma d.c.

Hydrocarbon emissions are measured using a Carle Instrument Model 0197 Series S analytical gas chromatograph (AGC). The heating system features a solid-state full proportional temperature controller capable of responding to temperature changes of less than 0.001°C. This controller operates high wattage heaters carefully matched with conductive thermal mass to give precise temperature control of columns, inlets, detectors and valves from ambient to 399°C with only a single digital temperature control.

All electronics, including the electrometer for the flame ionization detector (FID), the bridge/power supply for the thermal conductivity detector (TCD), and the temperature controller are modular for user convenience. Each

electronic module is removable as a unit so that exchange or service can be conducted promptly.

Particular features of the FID are very high sensitivity, unusually wide dynamic range, and location of high impedance connections and insulators to minimize the need for cleaning. The low volume TCD is designed for either thermistors or filaments, and the bridge/power supply adapts to either at the push of a switch. Inlets are designed to confine samples in the column and allow for both flash vaporization and on-column injection.

Mounting brackets are provided for up to three valves; one at ambient and two at controlled temperature. Ready accessibility of the column, detector, inlet and valve area are provided by the flip-open top.

All the AGCs are dual-column, dual-inlet instruments. Columns are 1/8-inch diameter. Columns are heated with an air bath which is surrounded and uniformly heated with a conductive metal enclosure. Detectors, valves and inlets are heated conductively through contact with aluminum plates permitting operation of these components at stable, differential temperatures above column temperature.

This model of the AGC is provided with a filament or thermistor thermal conductivity detector. The two different sensing elements are interchangeable and the power supply adapts to either with the push of a switch. The use of thermistors is advantageous for highest sensitivity below about 70°C, and in those cases where oxidation by sample components may be a problem with filaments. Filaments give higher sensitivity at temperatures above 70°C and also permit hydrogen to be used as carrier gas. The power supply provides constant current to maximize the dynamic range of the detector and to keep sensitivity constant under particular operating conditions. Attenuation is in binary steps and has a range of 1 to 1024 to provide an optimum interface with modern data handling equipment.

The kiln burning zone temperature was measured with an IRCON Modline Series R optical pyrometer. The instrument consists of two units - a Sensing Head and an Indicator Unit. These two units are joined by a signal cable. The Sensing Head senses the infrared radiation emitted by a heated object, and

supplies an electrical signal to the Indicator Unit. The Indicator Unit provides a signal, linear with temperature, to produce a front panel display of temperature in degrees. Linear signal outputs are also available to operate a variety of auxiliary devices.

The R Series Modline is a Two Color Pyrometer (also called a Ratio Pyrometer). It provides an advanced electronic system that measures temperature by comparison of infrared radiation levels at two carefully selected wavelengths. Temperature readings are based on the ratio of the two radiation signals.

Because it is sensitive to the ratio of radiation intensities at two wavelengths, rather than the absolute intensity of radiation at a single wavelength, the R Series Pyrometer is almost immune to error caused by emittance changes in target material, undersized objects that do not fill the field of view, and bursts of steam, dust, etc. in the sight path. For example, a burst of steam between the target and Sensing Head cuts down the infrared radiation reaching the Head. A conventional pyrometer would sense this as a decrease in temperature and falsely indicate a lower temperature. The R Series Pyrometer will also sense a decrease in radiation but if the decrease is the same at both wavelengths, it "computes" the same ratio between the two signals and continues to give accurate temperature readings.

Specifications:

Spectral Response: Two adjacent wavelength bands
Short wavelength - Narrow band centered on 0.95 microns
Long wavelength - Narrow band centered on 1.05 microns

Calibration Accuracy: Within 1% of full scale temperature

Ambient Temperature: Indicator/Controller - 50 to 130°F
Sensing Head - 30 to 130°F

Repeatability: Within 0.3% of full scale temperature

Signal Reduction Range (Caused by low emittance, non-resolved target or obliteration of target): Above 1500°F (800°C), will tolerate approximately 95% reduction in radiation intensity

Optical Resolution: D/50 or D/100, depending on model

Response Time (to 95% of full scale input)
At meter - 1 second

At output - 0.1 second standard; 0.01, 1.0 and 10 seconds optional

Standard Output: 0 to +100 mVdc, linear with temperature span
100 ohm source

Calibration: Greybody - fixed, factory set
ε-Slope - factory set for tungsten, field adjustable per customer option

Invalid Alarm: Visual Front Panel Indicator
Contact Closure rated as follows:
Resistive: 115/230 VAC, 5A
Inductive: 115 VAC, 2A; 230 VAC, 1A

Power Requirements: 115 or 230 VAC, ± 10%, 50/60 Hz 30 VA Max.
(Customer specified voltage)

Recording Instruments. The outputs of the five analyzers are presented on front panel meters and are simultaneously recorded on two Texas Instruments Servo/Riter II strip chart recorders. The recorder specifications are as follows:

Specifications:

Strip Chart Display
Chart Size: 9-3/4 inch
Accuracy: ± 0.25%
Linearity: < 0.1%
Line Voltage: 120V ± 10% at 60 Hz
Span Step Response: 1 sec

Digital Data Recording

An on-line Emissions Monitor Program was written for the Apple II Plus 48k computer to provide automatic digital data acquisition for real time monitoring of emissions data. The program provides a visual display including a time plot of selected data, prints the data on a character printer, and records the data on a magnetic disk. The data can be accessed later, off line, for further processing or plotting using other programs available for the Apple.

Recorded emissions data for the cement kiln testing included oxygen (percent O_2), carbon monoxide (ppm CO), nitric oxide (NO corrected to 3 percent O_2, ppm), carbon dioxide (percent CO_2), and sulfur dioxide (ppm SO_2). The optical pyrometer was wired into the Apple computer to record front end temperature.

2.1.2 Gaseous Sample Handling Equipment

The sample gas stream for analysis is withdrawn from the exhaust duct with a probe of one-half inch 316 stainless steel heavy wall tubing. Initially, the probes had 0.7 micron sintered stainless steel filters. Since the filters were continually plugged, an unfiltered probe was tried. The unfiltered probe also plugged but could be easily unplugged by back-flushing. It was decided to sample with the unfiltered probes and to blow-back with compressed air at the first indication of loss of sample flow. Also, it was found that the probe must be removed when rings were being blown from the kiln or any maintenance work on the kiln was being performed. Because the probe was located near the raw feed chute at the kiln exit, unplugging the probe became an hourly maintenance item.

The sample line was 3/8-inch nylon line connecting the probe to the sample conditioning system in the mobile laboratory. Positive displacement stainless steel diaphragm pumps located in the mobile laboratory furnish the motive power for the sampling. The flow system is divided into two branches: a heated side for measuring NO_x, SO_2, and HC and an unheated side for measuring CO, CO_2, and O_2. The heated sample passes through a heated filter, heated five-way selector valves and rotameters to the analyzer. The sample is delivered to the analyzers with high temperature metal bellows pumps. The unheated branch of the system contains a filter, a positive displacement diaphragm pump, a refrigerated condenser to reduce the sample dew point temperature to 35°F. The flow then passes through a five-way selector valve which allows for selection of zero gas, span calibration gas or sample gas to flow to the analyzers. The flow rate to each analyzer is measured and controlled with rotameters and flow control valves.

2.2 TEST FACILITY DESCRIPTION

The test facility for the subscale rotary kiln tests is located at a major California cement plant. The kiln, pictured in Figure 2-4, is 27 feet long and 15 inches inside diameter. The kiln produces clinker at an average rate of approximately 100 pounds per hour. Maximum clinker output was about 150 pounds per hour. The refractory brick lining is six inches thick near the burner and three inches thick for the remainder of the kiln length. The rotary kiln's speed is adjustable, but was operated at 2 rpm for these tests.

The host cement company completely refurbished the kiln, the raw feed system and the peripheral equipment. Modifications to the test site included: sealing the kiln/dust box interface, sealing the kiln/hood interface, modifying the raw feed inlet to the kiln, installing inlets for recirculated flue gas and heated secondary air at the clinker box, installing a high pressure/high capacity positive displacement blower, new motor for the induced draft fan, renovating the raw feed pelletizer and preparing the electrical system for operation. In addition to the modifications to the kiln and auxiliary equipment, the host company provided training for KVB personnel and laboratory facilities and assistance. The company also provided an optical pyrometer for measuring the flame zone temperature.

The kiln as originally constructed had no provision for heating the combustion air. In order to make the test program more realistic, preheated combustion air was required. In a full-scale commercial kiln the combustion air is preheated by the clinker cooler. A clinker cooler was considered, but complexity, size and cost required an alternate method of heating the combustion air. A metallic recuperator was purchased and installed in the system for preheating the combustion air. The flue gas for the recuperator was supplied by a supplemental gas-fired burner firing into an insulated process chamber. Combustion air temperature could then be varied by regulating the firing rate of the supplemental burner.

The kiln was originally designed for gas firing. A burner for firing pulverized coal and/or natural gas was designed, fabricated, and installed by KVB. A schematic of the burner is shown in Figure 2-5. The design of the burner was intended for varying burner parameters, including primary air

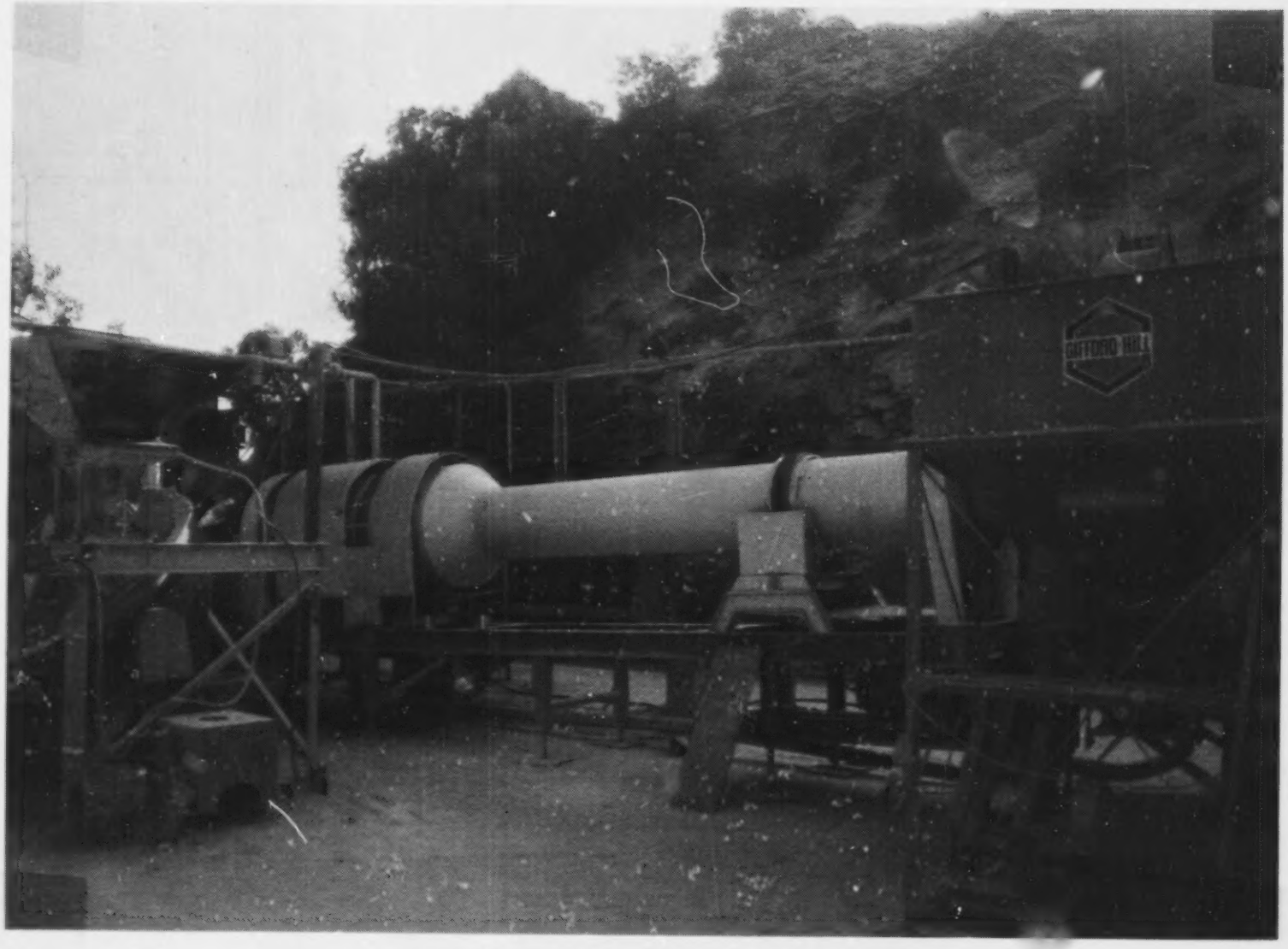


Figure 2-4. Subscale Rotary Cement Kiln.

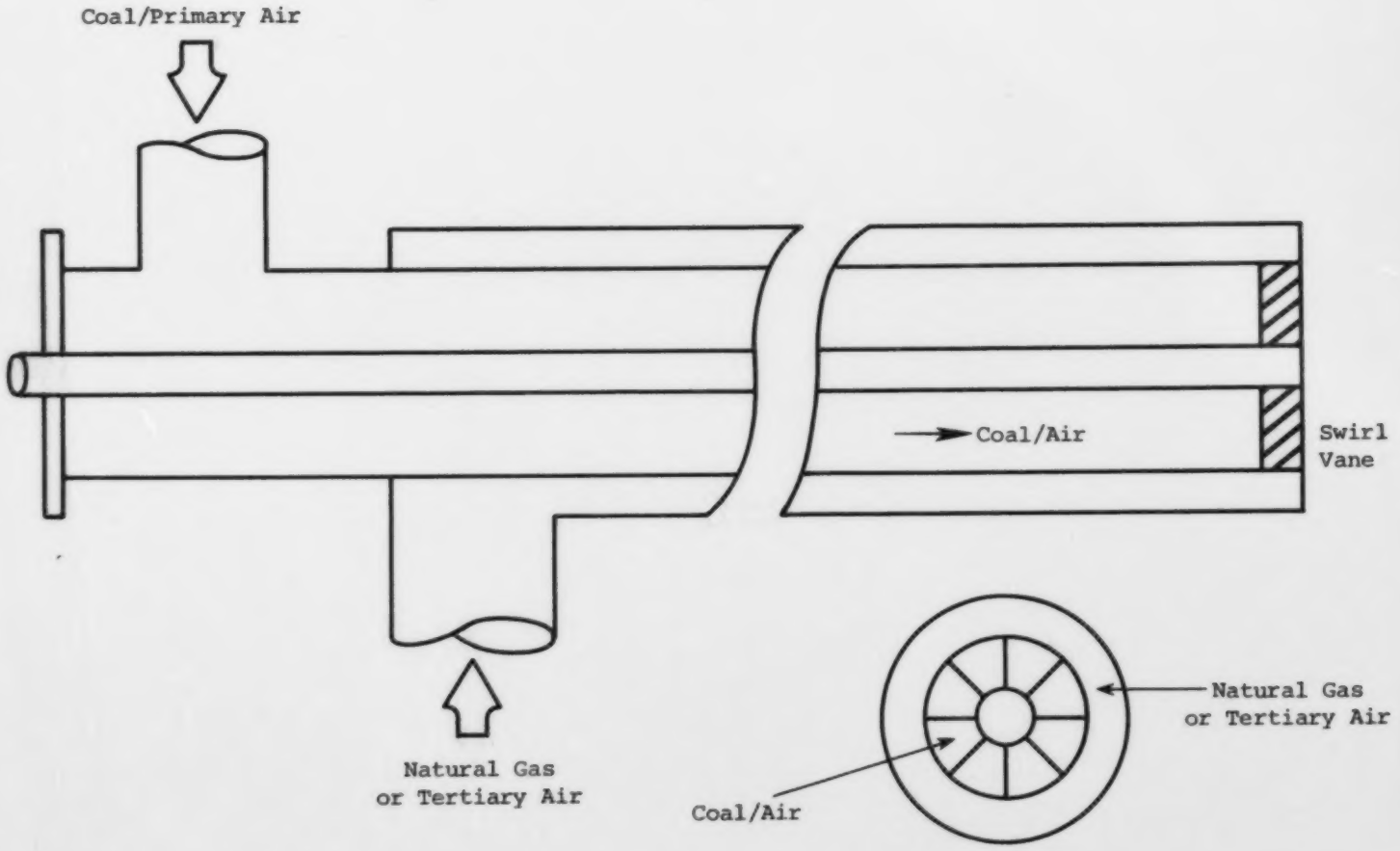


Figure 2-5. Schematic of Pulverized Coal Burner

velocity, insertion depth, and primary air/tertiary air distribution. Primary air velocity could be varied by inserting a spacer over the center tube. The insertion depth of the fuel and burner air into the kiln could also be varied. The burner air could be proportioned between the inner annulus primary air stream and the outer annulus tertiary air stream.

The kiln was fed pulverized coal by means of a vibrated volumetric screw feeder. The feeder incorporates a vibrating hopper delivering coal to a rotating and vibrating feed screw. The screw speed is variable in stepless increments over a 10 to 1 range. The hopper was modified to increase the storage volume to approximately 8 cubic feet. A pressure balance line was installed to balance the pressure in the coal bin with the primary air pressure.

A flue gas system was adapted to the kiln system. Flue gas was recirculated by a high temperature fan from the duct downstream of the dust box to the kiln front. Flow rate was measured with a sharp edged orifice. Because of the large amount of infiltration in the dust box the flue gas oxygen content was approximately 15 percent. A two-inch pipe was subsequently inserted through the dust box into the kiln exit to withdraw flue gas (see Figure 2-6). The recirculated gas composition then matched the kiln exit gas composition. The piping was then plumbed into a drop-out drum to remove entrained dust from the flue gas stream. Flue gas was also plumbed into the tertiary air manifold so that flue gas could be injected directly into the burning zone.

The general arrangement of the system components is shown in Figure 2-7. A flow schematic of the system showing major measurements and flow patterns is presented in Figure 2-4.

2.3 KILN OPERATION

KVB personnel were trained in the operation of the kiln by supervisory personnel at the cement plant. Subsequent to the training, KVB operated the kiln and conducted the test program.

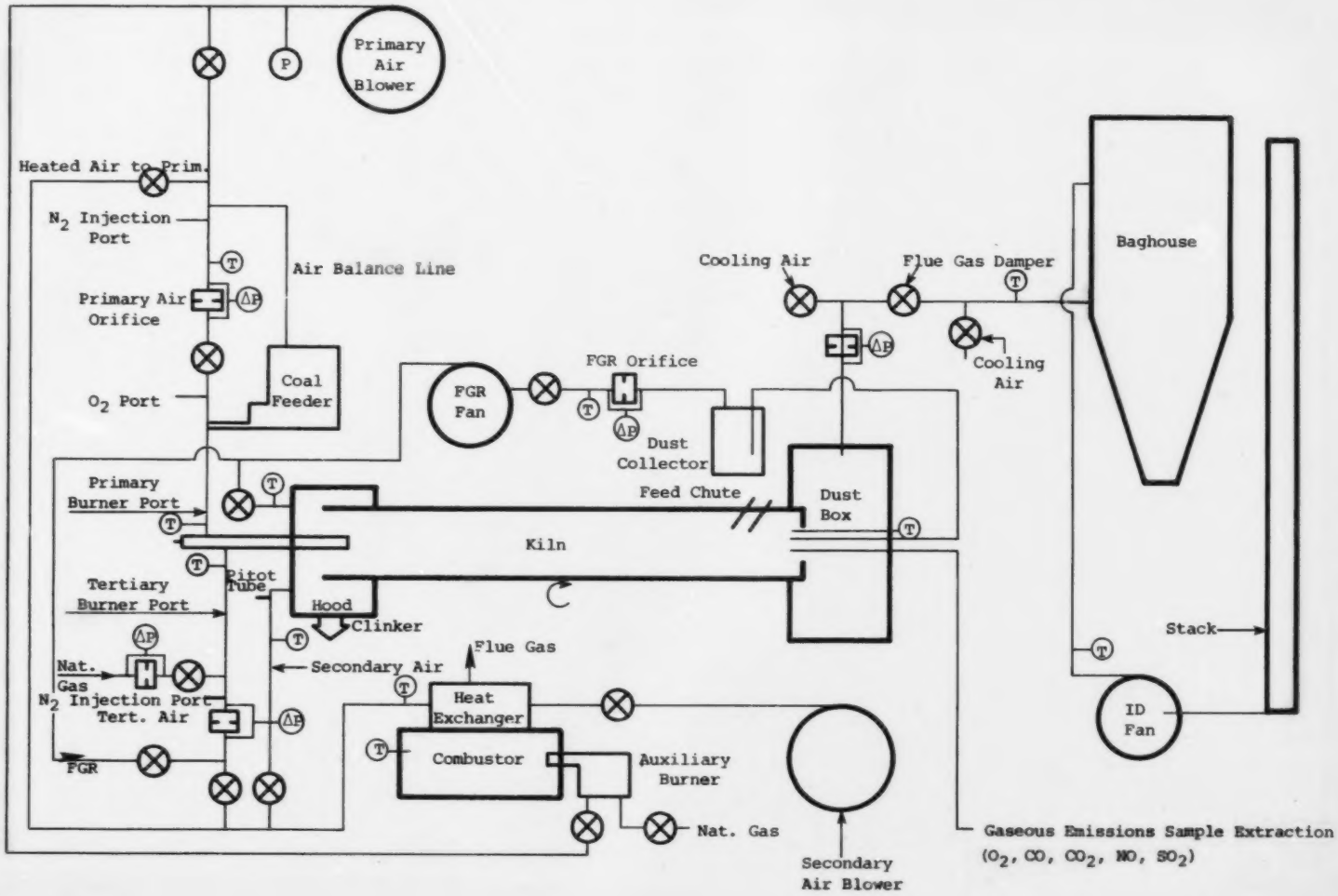


Figure 2-6. Schematic of Test Facility Subscale Cement Kiln

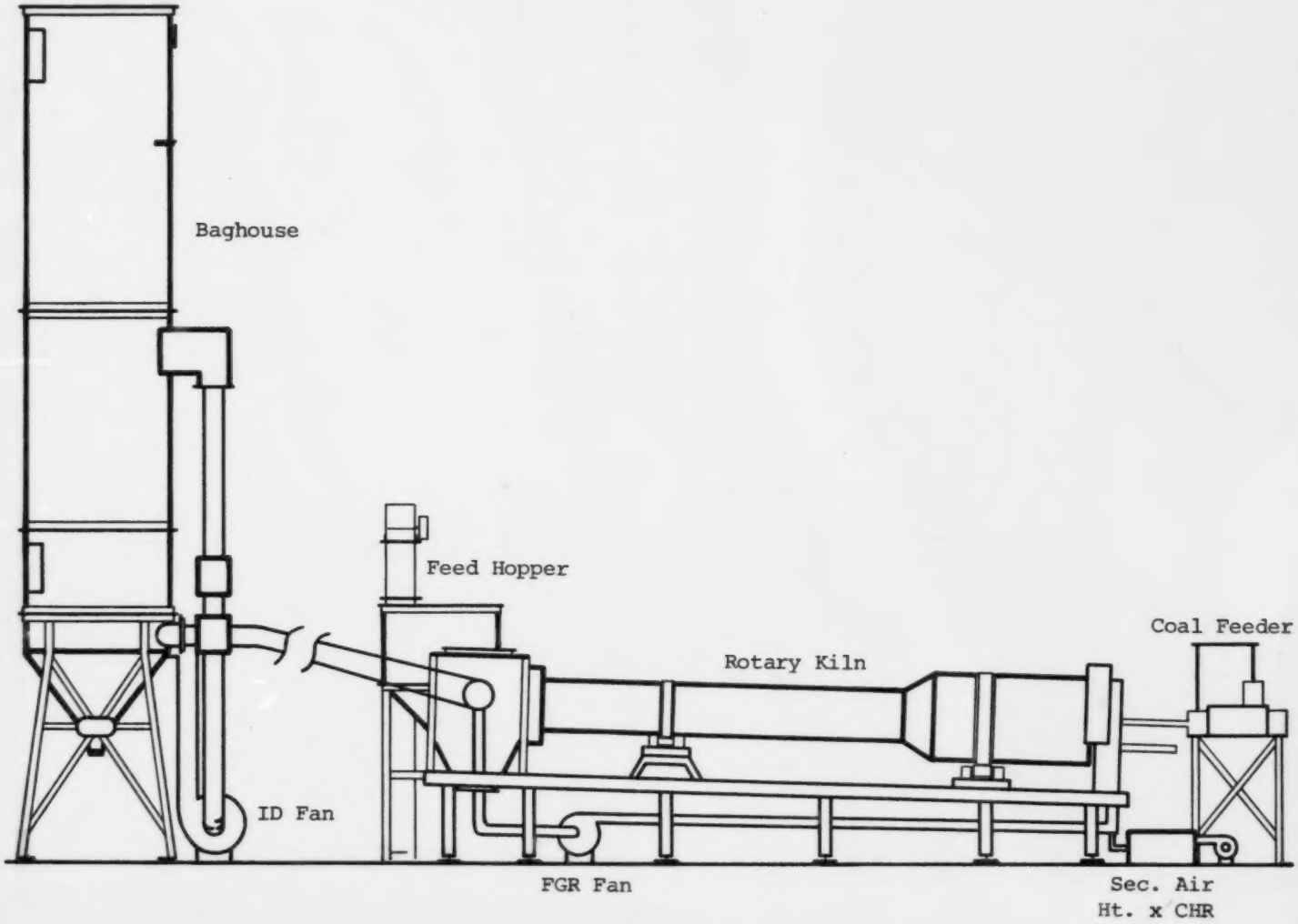


Figure 2-7. Arrangement of Kiln System Components

Raw feed was delivered to the test site in a bulk feed trailer. The trailer was pressurized, using an air compressor, to transfer feed into a hopper. The raw feed was then pelletized using a rotating disc pelletizer and transferred into the kiln feed hopper. After clogging of the feed pipe was encountered, the pellets were air dried and screened prior to loading into the feed hopper. The raw feed pellets were fed into the kiln using a vibrator and small bucket conveyor. Two raw feed samples were analyzed during the test period. These analyses are reported in Appendix A.

On cold startup, the kiln was heated slowly with natural gas firing, without introducing the raw feed. After the feed was introduced, the firing rate was increased to further raise the temperature until an acceptable clinker was produced. Secondary and primary air flows and temperatures were adjusted during kiln heatup to predetermined levels and allowed to stabilize. After the required temperatures and flow rates were achieved and stabilized, the switch to coal firing was made. As the coal feed rate was increased, the natural gas flow was diminished to maintain a constant kiln temperature. An engineer had the responsibility of setting and maintaining all combustion related controls.

The coal burned was taken from the host company coal pile and pulverized. Appendix B presents the proximate and ultimate analysis of the western bituminous coal. The coal was pulverized to a fineness of 20 percent residue on 200 mesh, packaged in 50 lb bags and delivered in 55 gallon drums to the test site. When the kiln was operating on coal, the hopper was filled by removing the cover and emptying one or more bags into the hopper.

One of the primary goals of this program was to generate acceptable clinker under both natural gas and coal firing conditions. Typical front end kiln temperatures of 2600°F or more were required to generate acceptable appearing clinker. Although front end temperature for coal firing was typically 200 to 300°F greater than gas firing, there was no significant quantitative difference between the clinker free lime analyses for gas and

coal firing. The free lime was higher than acceptable levels, due in part to the low residence time of the feed (less than one hour) in the subscale cement kiln. The residence time was calculated from an empirical equation proposed by Gibb (Reference 2) and is shown in Appendix C. Residence time in the full scale kilns ranges from two to four hours.

SECTION 3.0

TEST RESULTS

This section presents the results of the gaseous emissions measurements made with the kiln firing natural gas and with pulverized coal. Section 3.1 is devoted to test results with natural gas firing and Section 3.2 is devoted to test results with coal firing.

3.1 TEST RESULTS WITH NATURAL GAS FIRING

The initial training of KVB personnel on kiln operation took place with the original kiln burner installed. After the basic kiln operation was learned, this burner was then removed and the KVB burner installed. A number of parametric tests were then conducted with the KVB burner firing natural gas. The primary purpose of these tests was the checkout and evaluation of the various subsystems such as the combustion air preheat and the flue gas recirculation system.

Table 3-1 presents a summary of the emissions data and the conditions for the natural gas firing tests. This table also shows the maximum NO reduction from the baseline test. As indicated in this table, flue gas recirculation is a very effective NO reduction technique when firing natural gas.

3.1.1 Baseline Tests

After the kiln operation was checked out and all systems were operating, gas baseline tests were conducted. The effect of kiln exit O_2 on NO emissions is shown in Figure 3-1 for ambient combustion air and combustion air temperature of 1000°F. These data show that the NO emission rate is very sensitive to kiln exit O_2 with both ambient temperature combustion air and high temperature combustion air. The slope of these curves shows that for ambient combustion air, a 1 percent decrease in exit O_2 results in approximately 46 ppm decrease in NO emissions. NO emissions with preheated combustion air are more sensitive to exit O_2. A 1 percent decrease in O_2

TABLE 3-1. SUMMARY OF TEST RESULTS: GAS FIRING - SUBSCALE CEMENT KILN

Test Series		SA Temp °F	SA Temp K	% Primary Air	% FGR	Fuel Firing Rate MW	Fuel Firing Rate (10^6 Btu/hr)	Kiln Exit O_2 (%, dry)	NO (ppmv, @ 3% O_2, dry)	CO_2 (%, dry)	Maximum % NO Reduction from Baseline
PA/SA[b] Variation (20/80)	Baseline	1100	867	19.1	0	0.21	(0.70)	2.0	640	11.2	
		900	756	↓			↓	↓	600	↓	
		600	589						400		64.4
		300	422						243		
		Amb.		↓			↓	↓	228	↓	
PA/SA Variation (33/67)	Baseline	1200	922	33.0	0	0.21	(0.70)	2.0	300	11.5	
		600	589	↓			↓	↓	194	↓	
		300	422						180		43.3
		Amb.		↓			↓	↓	170	↓	
SA[c] Temp. Variation	Baseline	1000	811	14.6	0	0.19	(0.64)	2.0	404	14.2	
		900	756	↓			↓	↓	419	↓	
		800	700						364		47.5
		700	644						350		
		Amb.		↓			↓	↓	212	↓	
FGR[d]	Baseline	1168	904	28.0	0	0.19	(0.64)	2.0	340	15.8	
		↓		↓	21.6		↓	↓	163	↓	
					28.6				135		70.6
					32.6				110		
		↓		↓	33.8		↓	↓	100	↓	

[a] All CO data for the nominal O_2's listed are less than 200 ppmv.

[b] PA: Primary Air

[c] SA: Secondary Air

[d] FGR: Flue Gas Recirculation

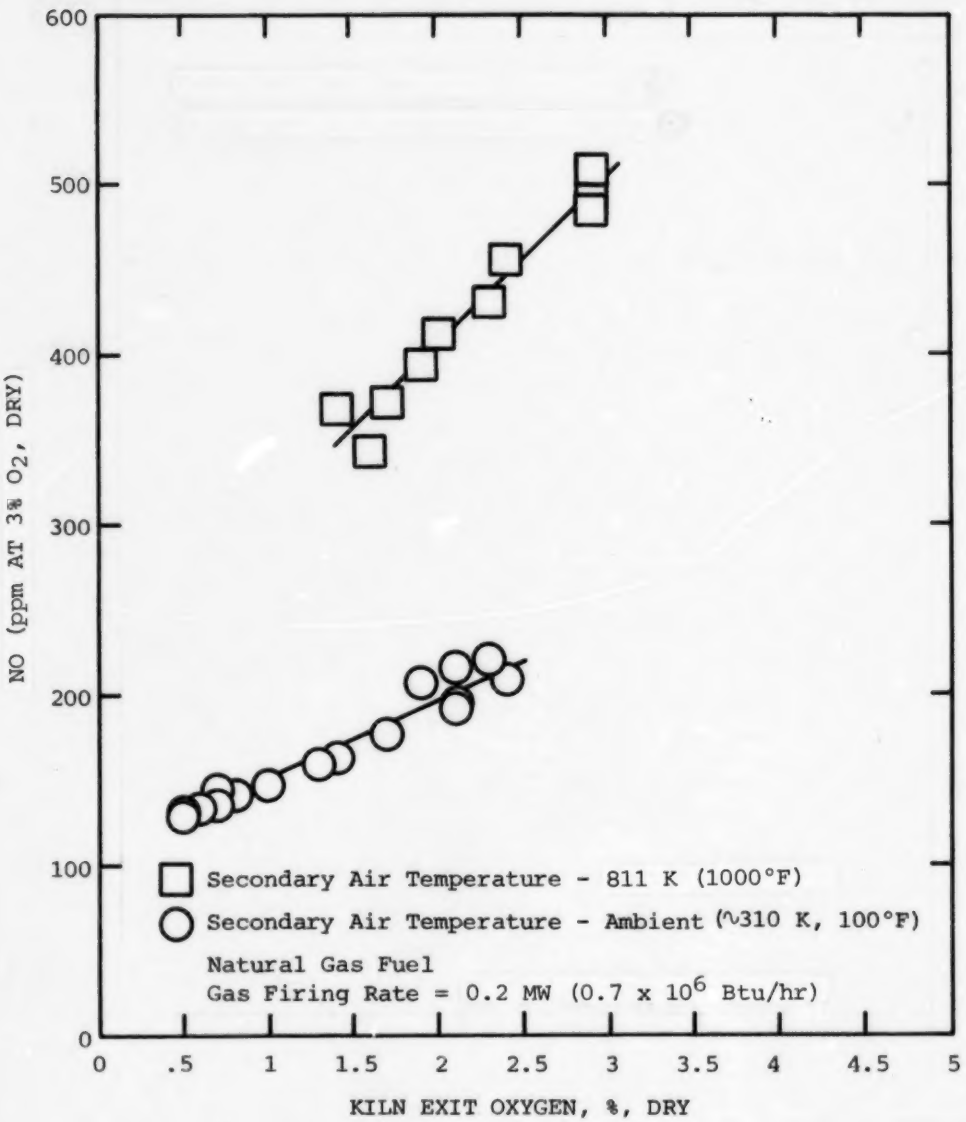


Figure 3-1. The Effect of Kiln Exit Oxygen on NO Emissions

results in approximately 99 ppm decrease in NO emissions. A linear regression analysis of the data was performed for both the ambient temperature and high temperature cases. Both conditions showed a very good linear correlation. For the ambient temperature case, the coefficient of determination, r^2, was 0.953 and the regression coefficients, a and b, were 104.5 and 46.4 respectively. For the 811 K (1000°F) case the coefficient of determination, r^2, was 0.949 and the regression coefficients were 208.8 and 98.8. A multiple variable linear regression was also performed with NO emissions as the dependent variable and kiln O_2 and secondary air temperature as the independent variables. A very good correlation was achieved from this analysis. The coefficient of determination was 0.989 and the regression curve was:

$$NO(ppm) = 87.7 + 45.3\ (O_2,\ \%) + 0.16\ (T_{SA},\ °F)$$

3.1.2 Primary/Secondary Air Ratio Variation

Tests were conducted in which the ratio of primary to secondary air was varied and the resultant NO emissions measured. For the KVB burner, the gas was introduced through the outer annulus shown in Figure 2-5. Primary air was introduced through the central annulus which included a swirl vane at the burner tip. Three levels of primary to secondary air were evaluated. The levels were 15 percent primary/85 percent secondary air, 20 percent primary/80 percent secondary air, and 33 percent primary/67 percent secondary air. For each primary/secondary air ratio the secondary air preheat was varied from ambient to 1100-1200°F. Figure 3-2 shows the results of these primary/secondary air variations for a firing rate of approximately 700,000 Btu/hr.

The data presented in Figure 3-2 show that the NO emission levels are significantly higher when the primary air is about 20 percent of the total air flow than for other conditions. The NO emission level is shown in Figure 3-3 as a function of the primary to secondary air ratio for a secondary air/temperature of 811 K (1000°F). These data clearly show that the NO level peaks at approximately 20 percent primary air flow. At levels less than 20 percent, the flame intensity (mixing) is less resulting in lower NO emissions. At primary air flow greater than 20 percent, the degree of mixing is

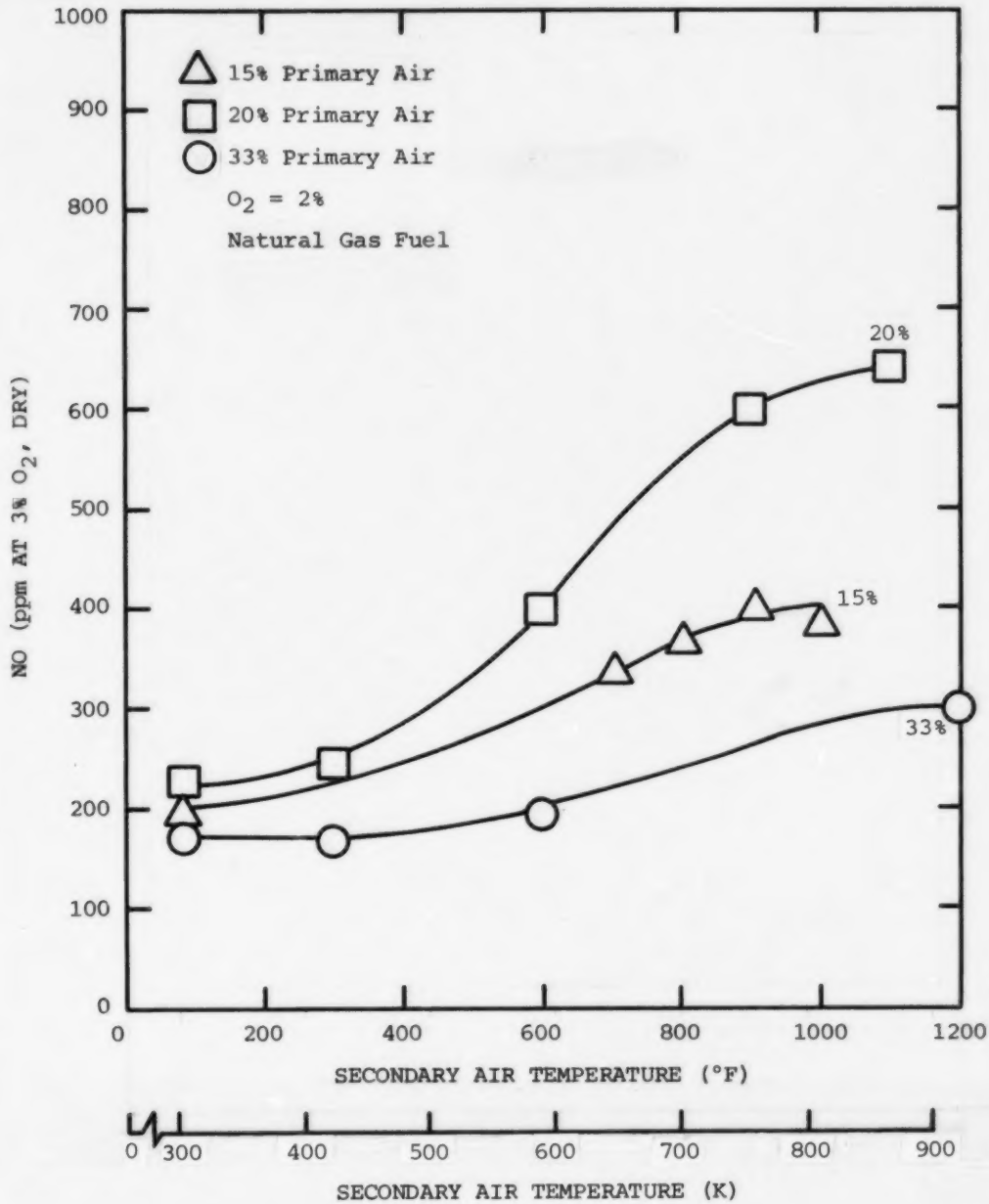


Figure 3-2. The Effect of Secondary Air Temperature on NO Emissions

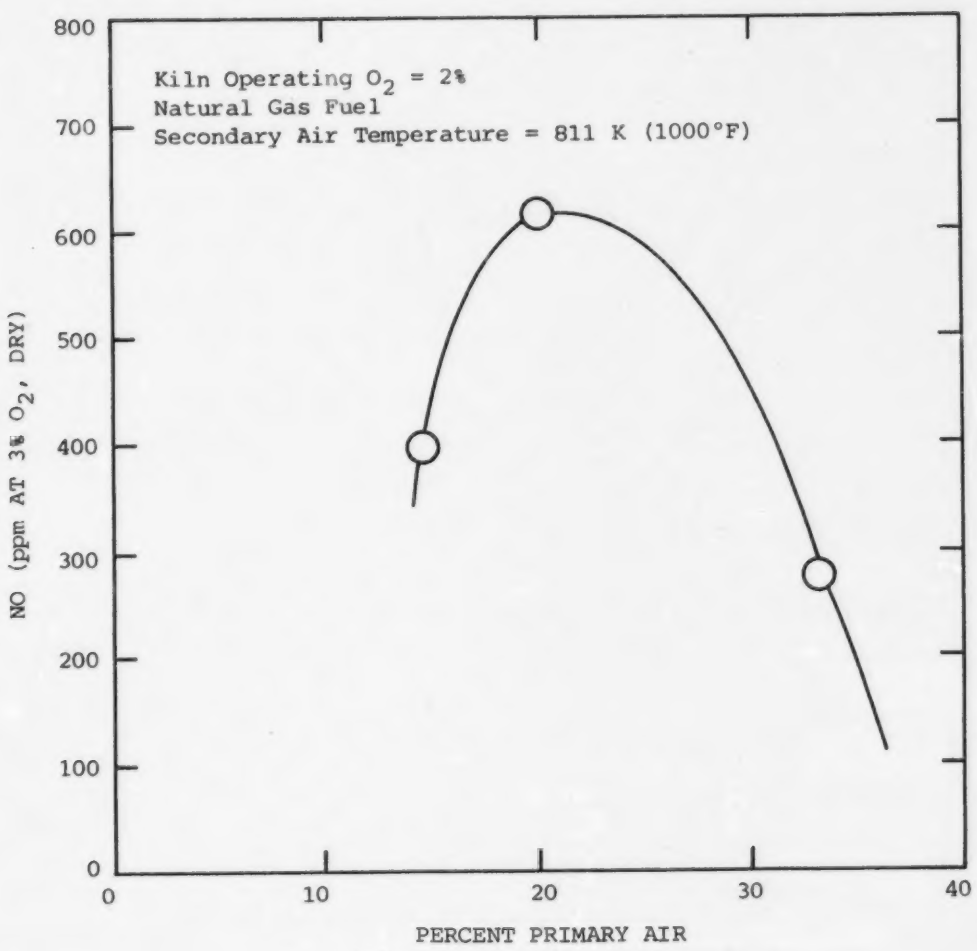


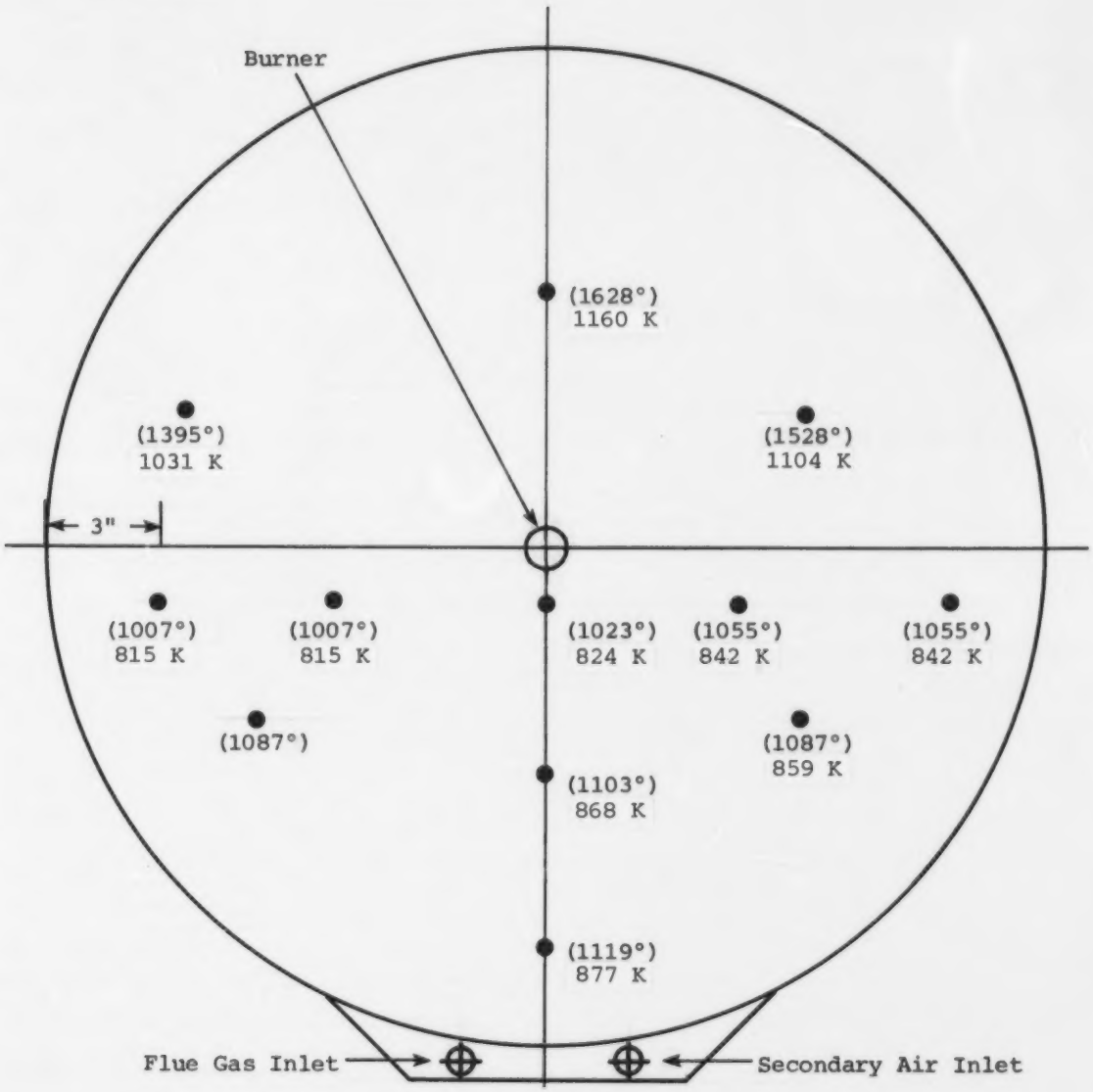
Figure 3-3. The Effect of Primary to Secondary Air Ratio on NO Emissions for Natural Gas Combustion

high due to higher velocities, but this is overshadowed by a larger amount of relatively cold air being introduced into the flame zone as primary air.

3.1.3 Effect of Combustion Air Preheat

Tests were conducted to evaluate the effect of combustion air preheat on the NO emissions from the kiln. Secondary combustion air was heated using a supplementary fired metallic recuperator. The maximum secondary air temperature achievable with this heat exchanger was approximately 950 K (1250°F). The limiting factor was the maximum design flue gas inlet temperature of 1083 K (1500°F). Secondary combustion air temperature was adjusted by varying the supplemental burner firing rate. For the natural gas fired tests, the secondary combustion air temperature was varied from ambient to 811 K (1000°F).

At the beginning of the air preheat variation tests, a series of measurements was made to determine the temperature variation in the kiln hood due to ambient air infiltration. A suction pyrometer with a platinum-platinum/rhodium thermocouple was used to measure gas temperature in the hood. The measurements were made at the exit plane of the burner which was approximately two feet from the outside of the kiln. The temperature profile is shown in Figure 3-4. The temperature of the secondary air was measured immediately before the entrance to the hood with a chromel/alumel thermocouple. For this test the secondary air temperature was (867 K) 1100°F. The gas temperatures were quite uniform at the burner exit with the temperature being higher above the burner, as expected. The effect of combustion air temperature on NO emissions was shown in Figure 3-2 for a firing rate of approximately 0.21 MW (700,000 Btu/hr). The kiln exit O_2 for these tests was 2 percent. As the figure shows, a substantial increase in NO emissions is experienced as the air temperature is increased from ambient to 1000°F. The NO emissions at elevated temperatures 756 K to 867 K (900 to 1100°F) are nearly double the concentration measured at ambient conditions. Figure 3-2 also shows the effect of combustion air temperature on NO emissions for different primary/secondary air ratios. As discussed in a previous paragraph,



All Readings at Burner Exit Plane
Sec. Air Temp. at Hood = 867 K (1100°F)
Air Temp. directly above Clinker Chute = 732 K (857°F)

Figure 3-4. Suction Pyrometer Temperature Measurements at Burner Exit Plane

at a given value of secondary air temperature the NO emission level peaks at approximately 20 percent primary air flow. The reason for this was explained in paragraph 3.1.2.

3.1.4 Flue Gas Recirculation

The FGR system was initially checked out with natural gas firing in the kiln. The NO emissions as a function of flue gas percentage are presented in Figure 3-5. The secondary air temperature averaged 904 K (1168°F) and flue gas temperatures averaged 372 K (210°F). The flue gas was injected into the secondary combustion air and had a very pronounced effect on NO emissions. A 70 percent reduction in NO emissions was achieved with a recirculation rate of approximately 34 percent. More than 50 percent reduction was achieved with 22 percent recirculation. Recirculation rate was calculated as the ratio of recirculated flue gas mass flow rate ($\dot{M}_{fg}$) to the sum of primary air mass flow rate, ($\dot{M}_{pa}$), secondary air mass flow rate, ($\dot{M}_{sa}$), fuel flow rate, ($\dot{M}_{f}$) and recirculated flue gas mass flow ($\dot{M}_{fg}$):

$$\% \text{ FGR} = \frac{\dot{M}_{fg}}{\dot{M}_{pa} + \dot{M}_{sa} + \dot{M}_{f} + \dot{M}_{fg}} \times 100$$

A regression analysis was performed on the data from the FGR tests. A second order polynomial curve fit yield a coefficient of determination, r^2, of 0.993, indicating excellent correlation. The regression equation with the constant and coefficients is:

$$NO = 349.4 - 10.9\ (\% \text{ FGR}) + 0.11\ (\% \text{ FGR})^2$$

3.2 TEST RESULTS WITH PULVERIZED COAL

Initial coal firing tests were begun on July 27, 1982. The kiln was brought up to temperature by firing natural gas. After the secondary and primary air temperatures were stabilized at the target values, the coal feeder was started. After visual verification of coal flow, the gas flow was diminished and coal flow increased. This procedure continued until the gas flow

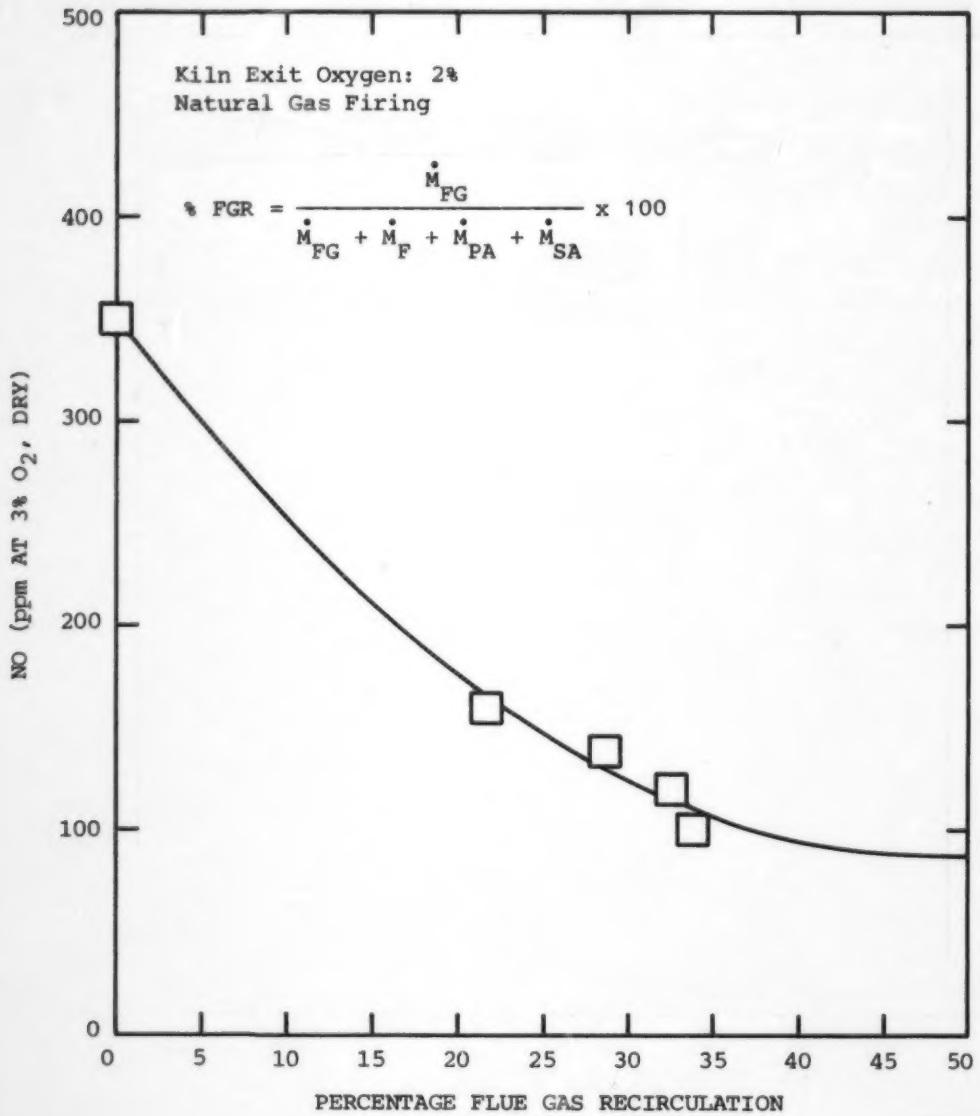


Figure 3-5. The Effect of Flue Gas Recirculation on NO Emissions

was completely shut off. At this condition the coal flame was unstable. Periodic blowoffs and re-ignition resulted in puffs and positive pressure at the kiln hood. Both primary and secondary air flow rates were adjusted without much success. The coal flame was unstable unless accompanied by a small amount of natural gas flow. Observation of the flame indicated that the coal flow rate was unsteady. The feeder screw was found to be nonconcentric with the sleeve resulting in an unsteady coal flow. The existing screw was subsequently replaced with a larger screw and a concentric sleeve. All subsequent tests had a substantially smoother coal flow.

After stable combustion was achieved, parametric tests were begun. Test series were conducted to evaluate the effect of secondary combustion air temperature, primary air velocity, primary/secondary air ratio, tertiary air injection, flue gas recirculation, and primary air vitiation on NO emissions. The results of these tests series are summarized in Table 3-2. The NO data are reported as parts per million NO corrected to a 3 percent O_2 dry, basis. Conversion of these numbers to equivalent pounds of NO (expressed as NO_2) per ton of clinker produced was not performed with one exception. The pounds NO as NO_2 per ton of clinker produced could not be accurately calculated due to uncertain coal feed rate and raw feed rate to the kiln. However, a sample calculation of pounds of NO as NO_2 per ton of clinker is provided in Appendix D to give the reader an approximate number under coal baseline conditions. The equation used is described in Reference 2.

3.2.1 Excess Air Variation

The effect of kiln excess air variation on NO emissions is shown in Figures 3-6 through 3-8 for combustion air temperatures of 1150, 1100, and 1000°F, respectively. These figures show, as did the gas-fired data, that the NO emission level is strongly dependent upon the operating O_2 level. At 1000°F combustion air temperature, a decrease in kiln exit O_2 of one percent results in a decrease in NO emissions of approximately 65 ppm. The other levels of air preheat exhibit similar trends although the absolute NO levels are higher with increasing combustion air temperatures.

A linear regression analysis was performed on the data for each level of air preheat. The correlation coefficient (r^2), calculated for each

TABLE 3-2. SUMMARY OF TEST RESULTS: COAL FIRING - SUBSCALE CEMENT KILN

Date	SA Temp. °F	SA Temp. (K)	PA Velocity fpm	PA Velocity (m/s)	% PA	Avg. O_2 (%)	Avg. CO (ppm)	Avg. NO (ppm corrected to 3% O_2, dry)	CO_2 (%)	Comments
7/27/82	1099	(866)	3338	(17)	28.4	3.5	25	753	16.4	Evaluate the effect of SA temperature on NO emissions; PA = constant O_2 = constant.
7/27/82	1003	(816)	3338	(17)	27.9	3.7	35	794	15.4	
8/04/84	1145	(892)	3338	(17)	29.4	3.8	559	826	14.6	
7/29/82	1167	(904)	3232	(16.4)	25.8	3.6	125	848	15.4	
8/12/82	1162	(901)	2950	(15)	21.0	3.7	148	806	15.5	Velocity variation; varied primary air flow. Secondary air ΔP was relatively constant.
8/12/82	1158	(899)	2504	(12.7)	19.3	3.6	396	643	17.8	
8/12/82	1166	(903)	2285	(11.6)	17.1	4.1	303	708	15.3	
8/12/82	1169	(905)	2128	(10.8)	16.2	5.3	963	773	15.5	
8/12/82	1161	(900)	2504	(12.7)	9.3	4.3	293	711	17.6	PA/SA variation tests. Varied PA flow and SA flow at constant O_2.
8/11/82	1187	(915)	2915	(14.8)	22.2	3.6	608	775	15.1	
7/29/82	1167	(904)	3232	(16.4)	25.4	3.6	136	822	15.8	
8/04/82	1153	(896)	3268	(16.6)	29.8	4.1	268	848	14.6	
8/04/82	1130	(883)	3440	(17.5)	30.1	5.4	452	847	13.8	Baseline for series to evaluate FGR, 0% FGR
8/04/82	1144	(891)	3390	(17.2)	29.7	5.0	79	836	16.4	19% FGR
8/04/82	1160	(900)	3440	(17.5)	30.1	5.6	167	788	13.7	21% FGR
8/10/82	1140	(889)	3120	(15.8)	22.5	2.9	481	727	15.3	Baseline for PA dilution tests
8/10/82	1160	(900)	2890	(21.7)	21.7	3.7	104	700	13.5	18% O_2 in PA — High PA Velocity
8/10/82	1140	(889)	3120	(15.8)	22.5	2.3	550	613	16.2	12% O_2 in PA — High PA Velocity
8/12/82	1160	(900)	2500	(12.7)	19.3	5.0	188	771	17.5	Baseline for PA dilution tests
8/12/82	1160	(894)	2500	(12.7)	18.4	4.0	87	635	17.9	15% O_2 in PA — Low PA Velocity
8/12/82	1160	(900)	2500	(12.7)	19.7	3.8	440	544	17.6	12% O_2 in PA — Low PA Velocity

PA: Primary Air

SA: Secondary Air

FGR: Flue Gas Recirculation

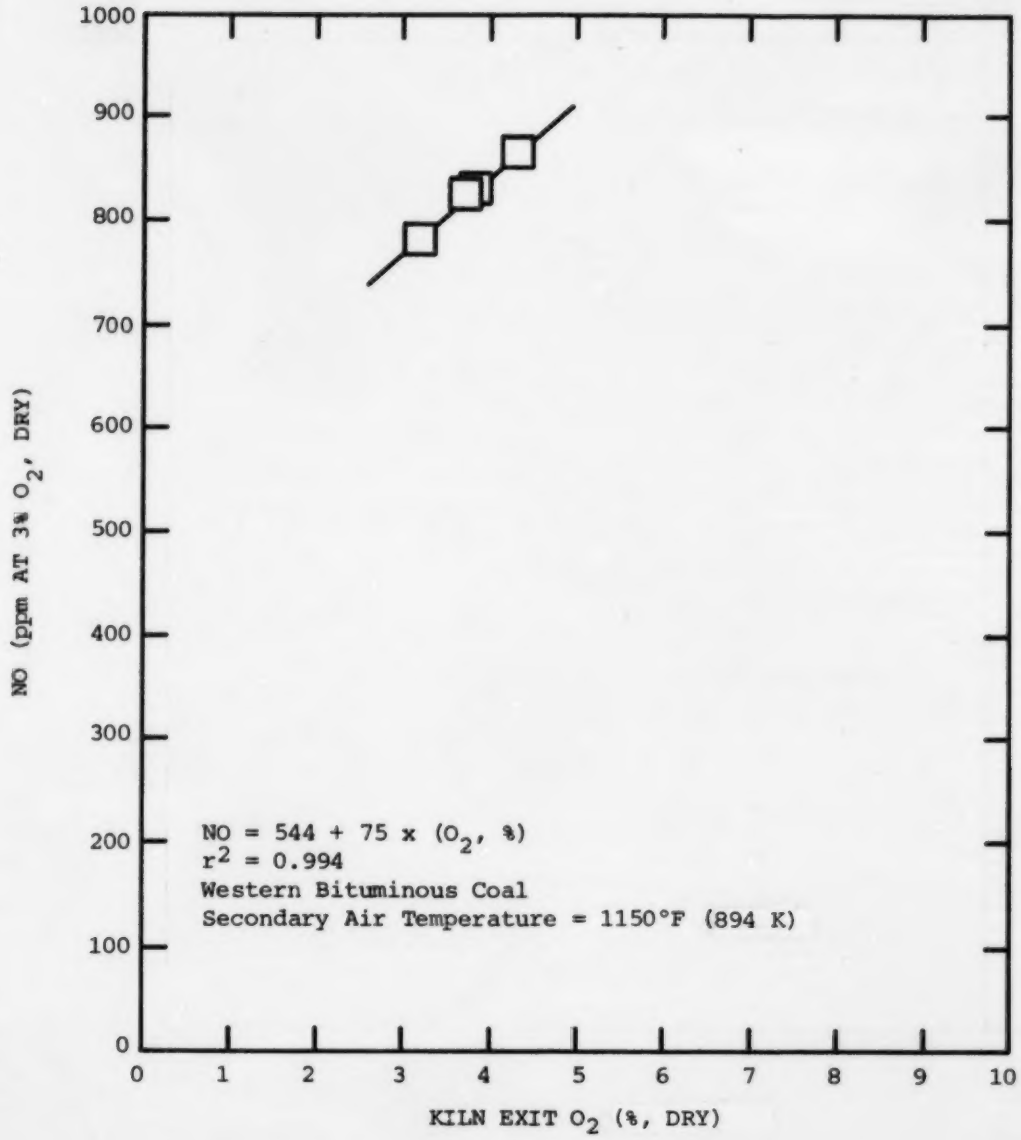


Figure 3-6. The Effect of Kiln Excess Oxygen on NO Emissions

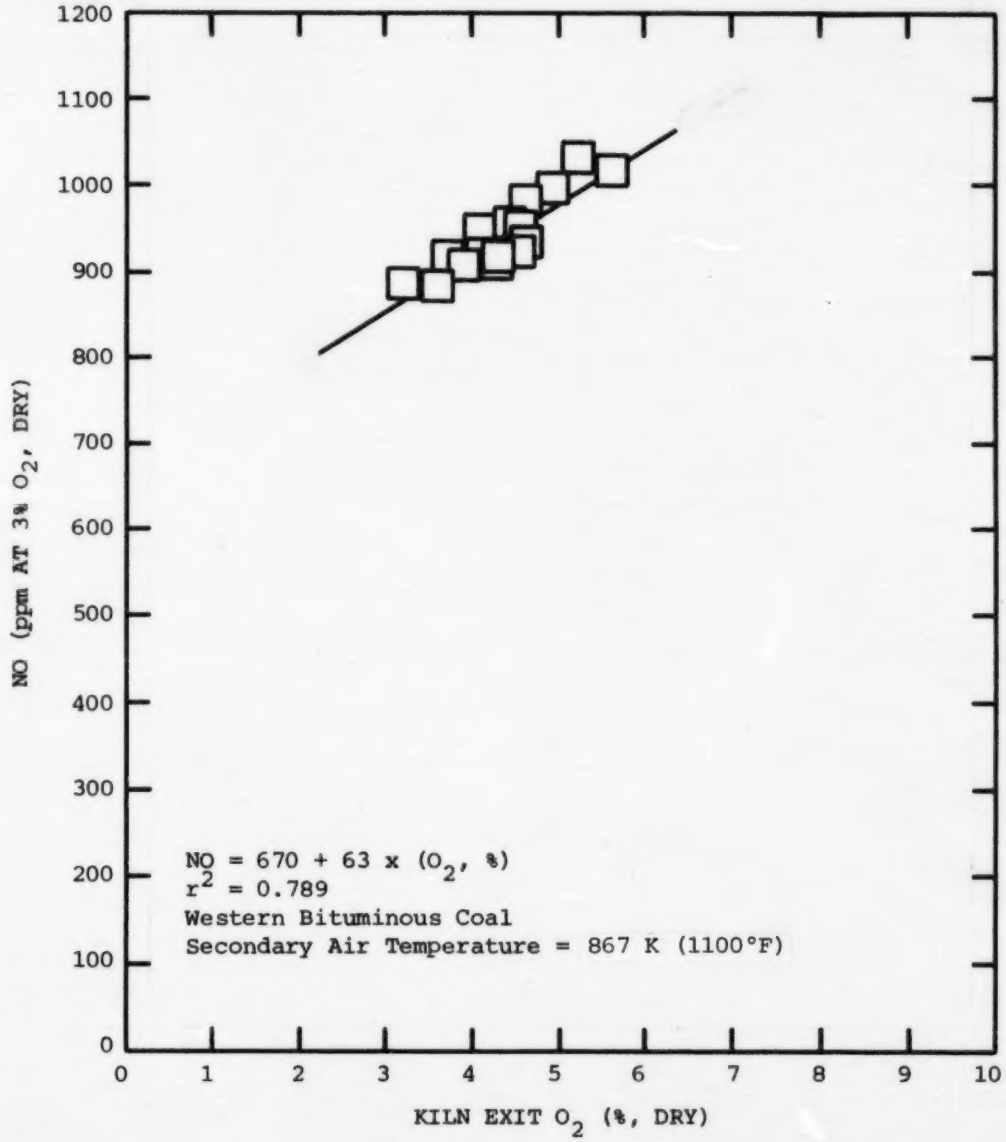


Figure 3-7. The Effect of Kiln Oxygen Level on NO Emissions

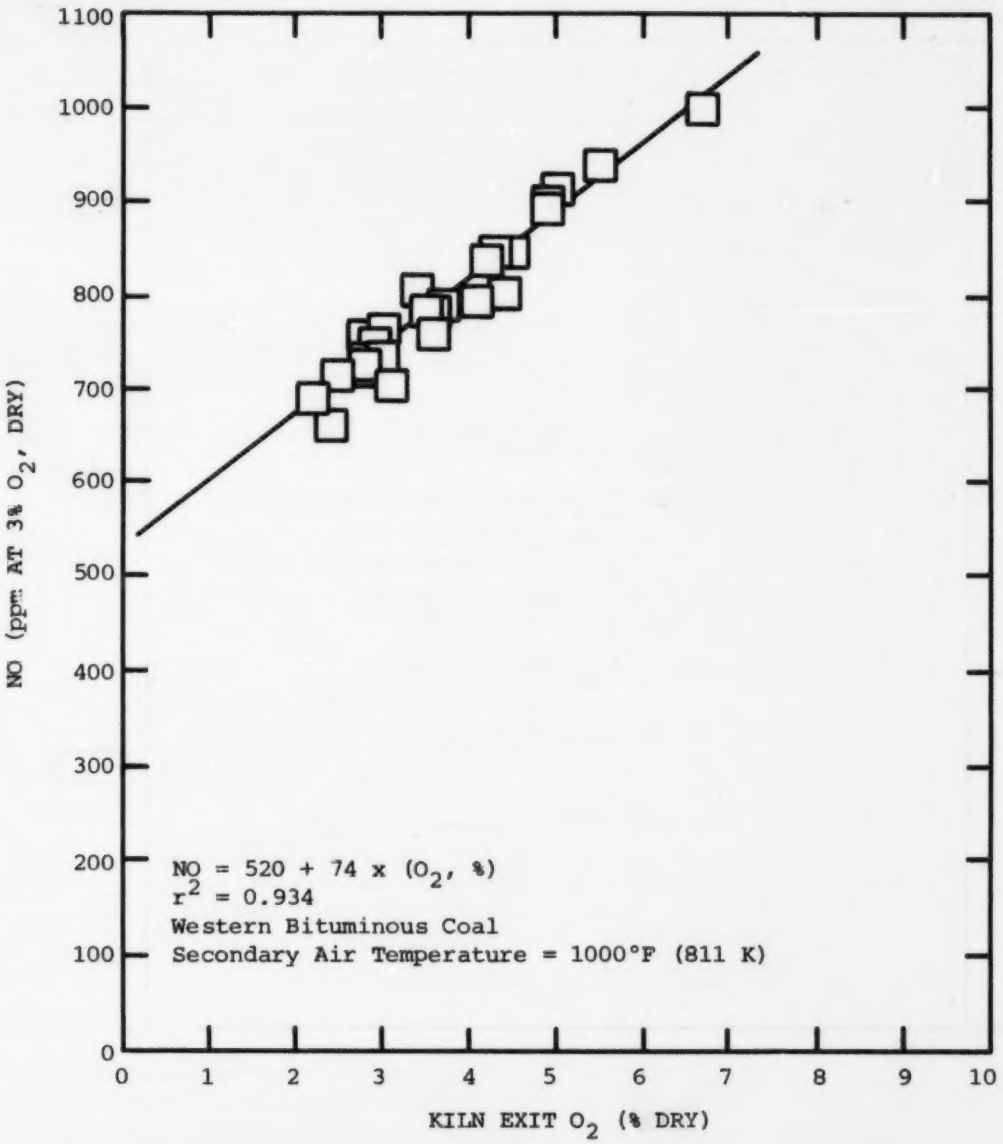


Figure 3-8. The Effect of Kiln Excess Oxygen on NO Emissions

condition, showed that a linear curve fit gives an excellent representation of the data. The solid lines through the data represent the calculated linear curve. Also shown on these figures are the slopes and correlation coefficients.

A multiple variable linear regression analysis was performed with the data shown in Figures 3-6 through 3-8. NO emission level was the dependent variable and kiln exit oxygen and secondary combustion air temperatures were the independent variables. A coefficient of determination, r^2, of 0.901 was calculated which shows very good correlation. The regression equation for NO as a function of O_2 and secondary air temperature is:

$$NO(ppm) = -164.6 + 77.2\ (O_2,\ \%) + 0.671\ (T_{SA},\ °F)$$

3.2.2 Secondary Air Preheat Variation

The effect of combustion air temperature on NO emissions was evaluated from approximately 811 K (1000°F) to 894 K (1150°F). Combustion air temperatures lower than 811 K (1000°F) tended to result in poor combustion of the coal (high CO, smoke levels). The data for the kiln operating at 3.5 percent O_2 are shown in Figure 3-9. The curve shows that the NO increased slightly as combustion air temperature increased. The slope of the curve is increasing with increasing temperature within the range of temperatures tested. The curve indicates that NO emissions are much more sensitive to combustion air temperature of 894 to 922 K (1150 to 1200°F). At the conditions shown in this figure, (i.e., 3.5 percent O_2 and 27 percent primary air flow), reducing the combustion air temperature from 906 to 839 K (1170°F to 1050°F) resulted in a reduction in NO of 10.7 percent (from 840 ppm to 750 ppm).

3.2.3 Primary Air Velocity Variation

Figure 3-10 shows the effect of primary air velocity on NO emissions for a typical kiln exit oxygen concentration (3.5 percent O_2). Primary air velocity was varied by decreasing the air flow rate from the baseline condition. The primary air burner area was kept constant for this series of tests.

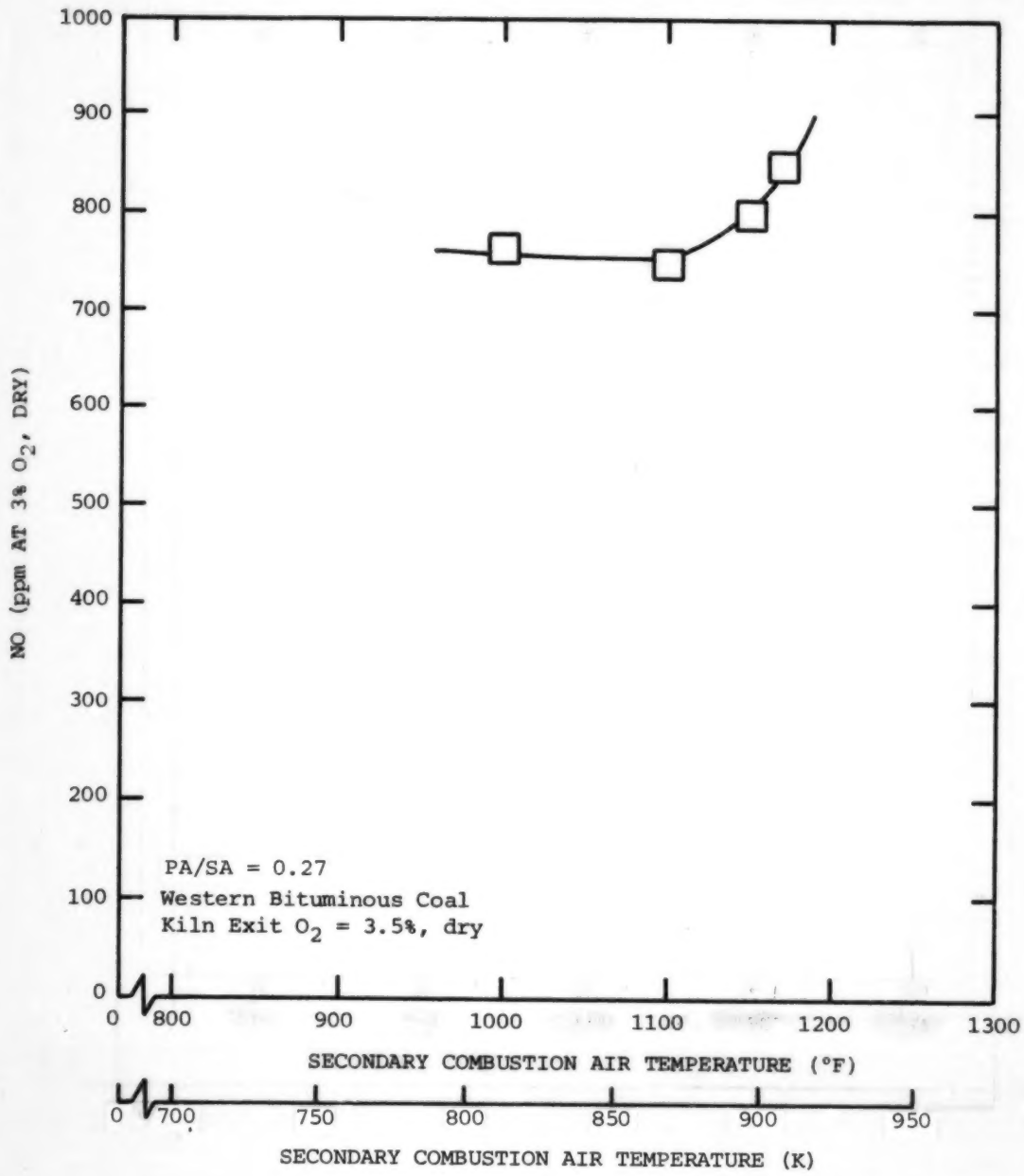


Figure 3-9. The Effect of Secondary Combustion Air Temperature on NO Emissions

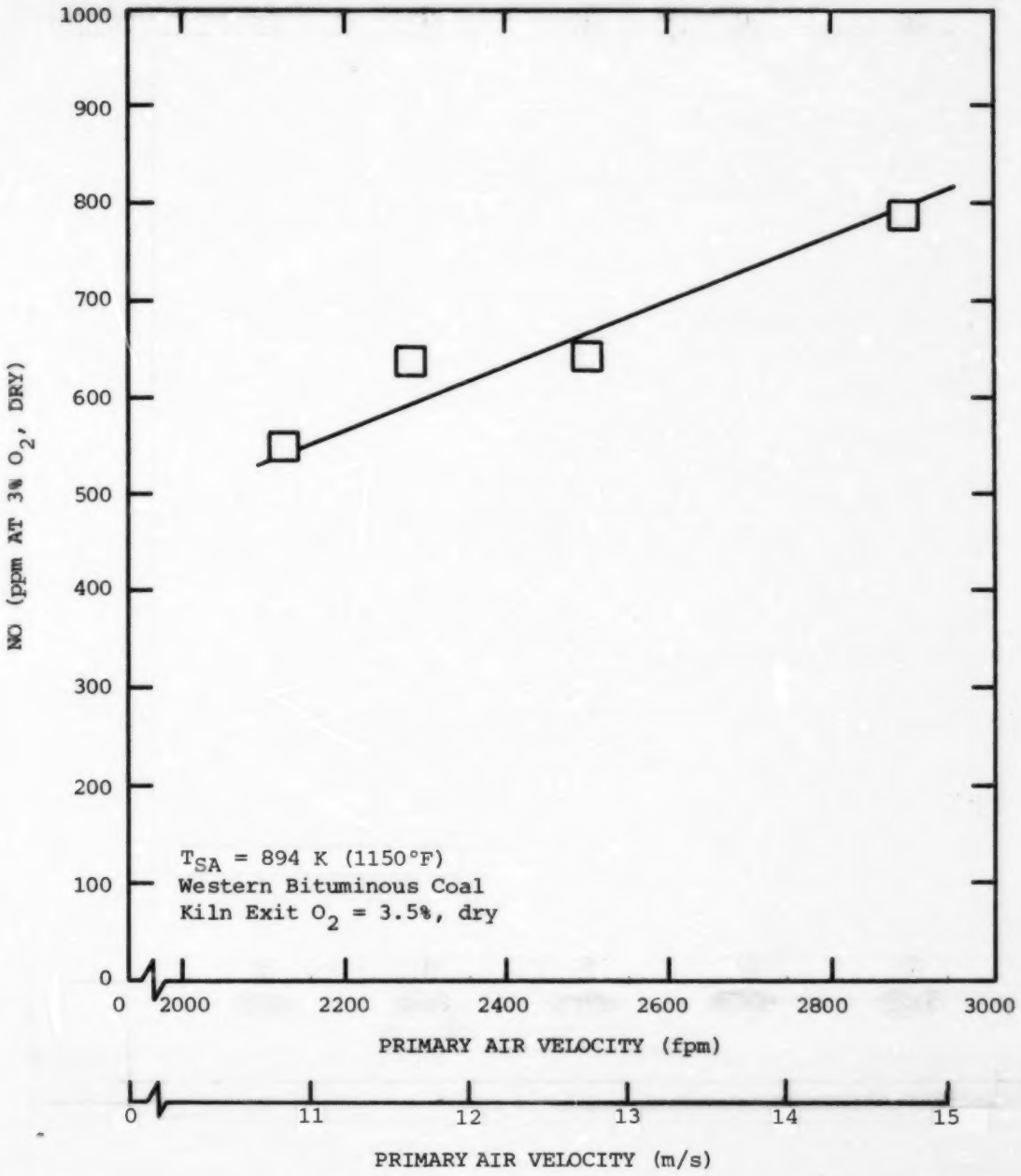


Figure 3-10. The Effect of Primary Air Velocity on NO Emissions

The results show that NO emissions at low primary air velocity 10.8 m/s (2128 fpm) are reduced by approximately 30 percent from the baseline condition 14.7 m/s (2890 fpm). The penalty for low primary air velocity is increased carbon monoxide emissions (Figure 3-11). As expected, combustion was not as complete with the longer lazier flame and lengthened burning zone effected by lowered primary air velocity.

It should be mentioned that another series of primary air velocity variation tests was attempted. This test series was based on a constant air flow rate and variable primary air burner area. A spacer was located about the burner's inner annulus to constrict the coal/primary air flow area and increase the mixture velocity. The extended flame length and flame instability with this velocity increase was unsatisfactory for the subscale kiln operation.

3.2.4 Primary/Secondary Air Ratio Variation

Figure 3-12 shows the impact of primary/secondary air variation on NO emissions for a typical kiln exit oxygen concentration (3.5 percent O_2). The curve indicates that NO emissions peak at approximately 23 percent primary/ 77 percent secondary air. As the primary air velocity is decreased, the NO emission level decreases due to poorer mixing in the primary flame zone. At primary to secondary ratios greater than about 23 percent, the effect of increased mixing from higher velocities is overshadowed by the effect of larger amounts of relatively cold air being introduced into the flame zone. Gas firing also showed the trend of peak NO emission levels at a 20 percent primary/80 percent secondary air ratio with decreasing NO emissions at ratios above and below 20 percent.

3.2.5 Tertiary Air Injection Test Series

Figure 3-13 shows the effect of tertiary air and vitiated tertiary air on NO emissions for a typical kiln exit oxygen concentration (3.5 percent O_2). Tertiary air stabilized the coal flame, but increased NO emissions 6.5 percent at 10 percent tertiary air. The increase is expected with a

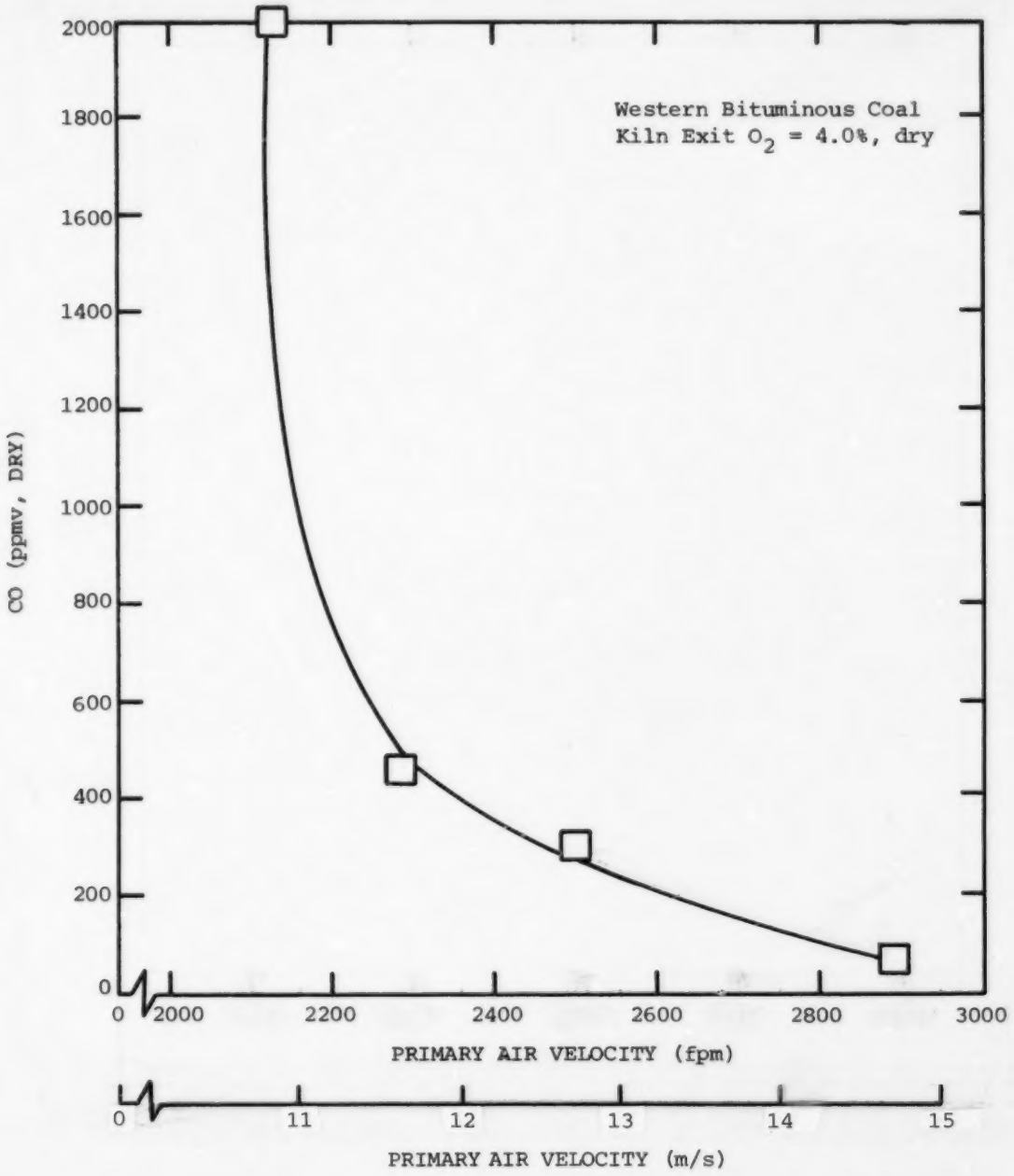


Figure 3-11. The Effect of Primary Air Velocity on CO Emissions

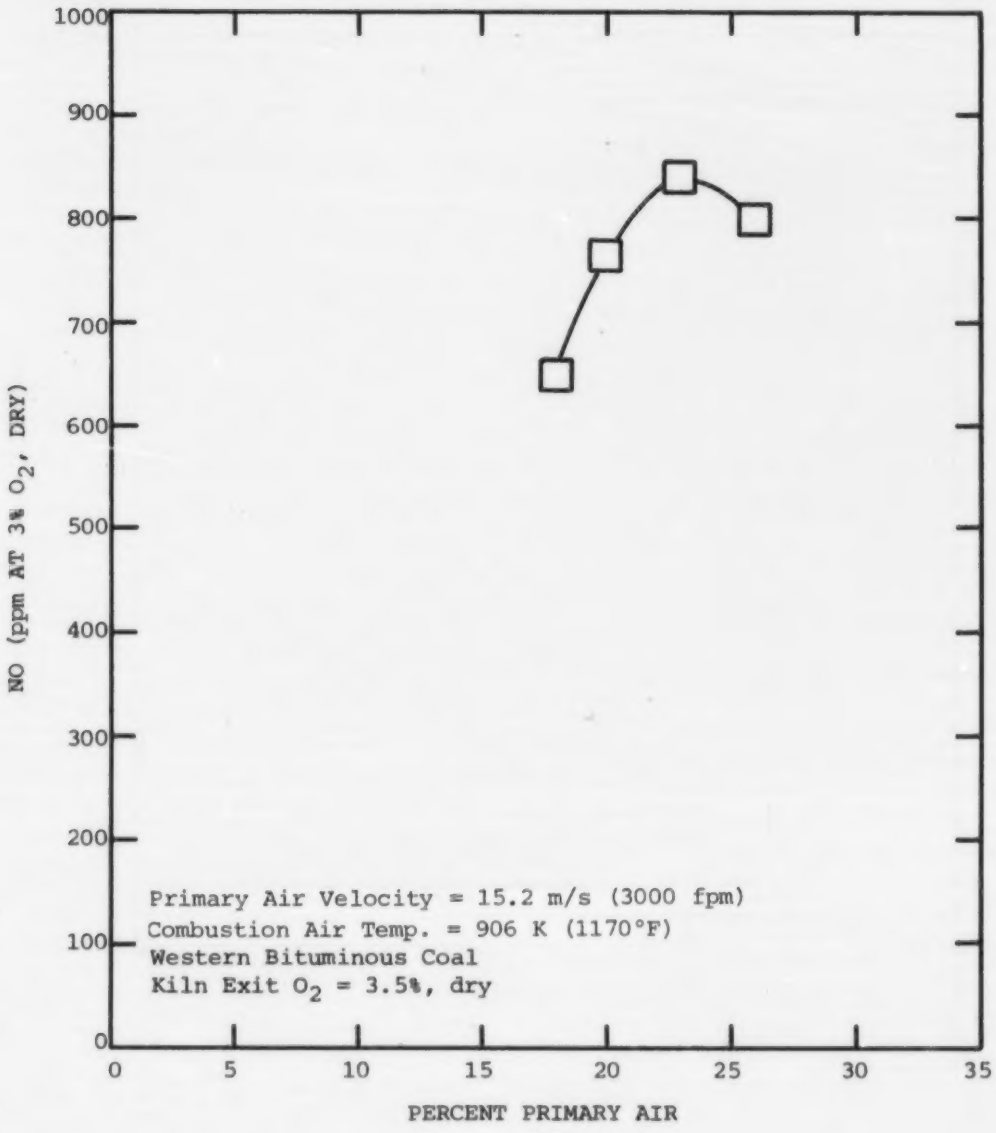


Figure 3-12. The Effect of Coal Primary Air/Secondary Air Ratio on NO Emissions

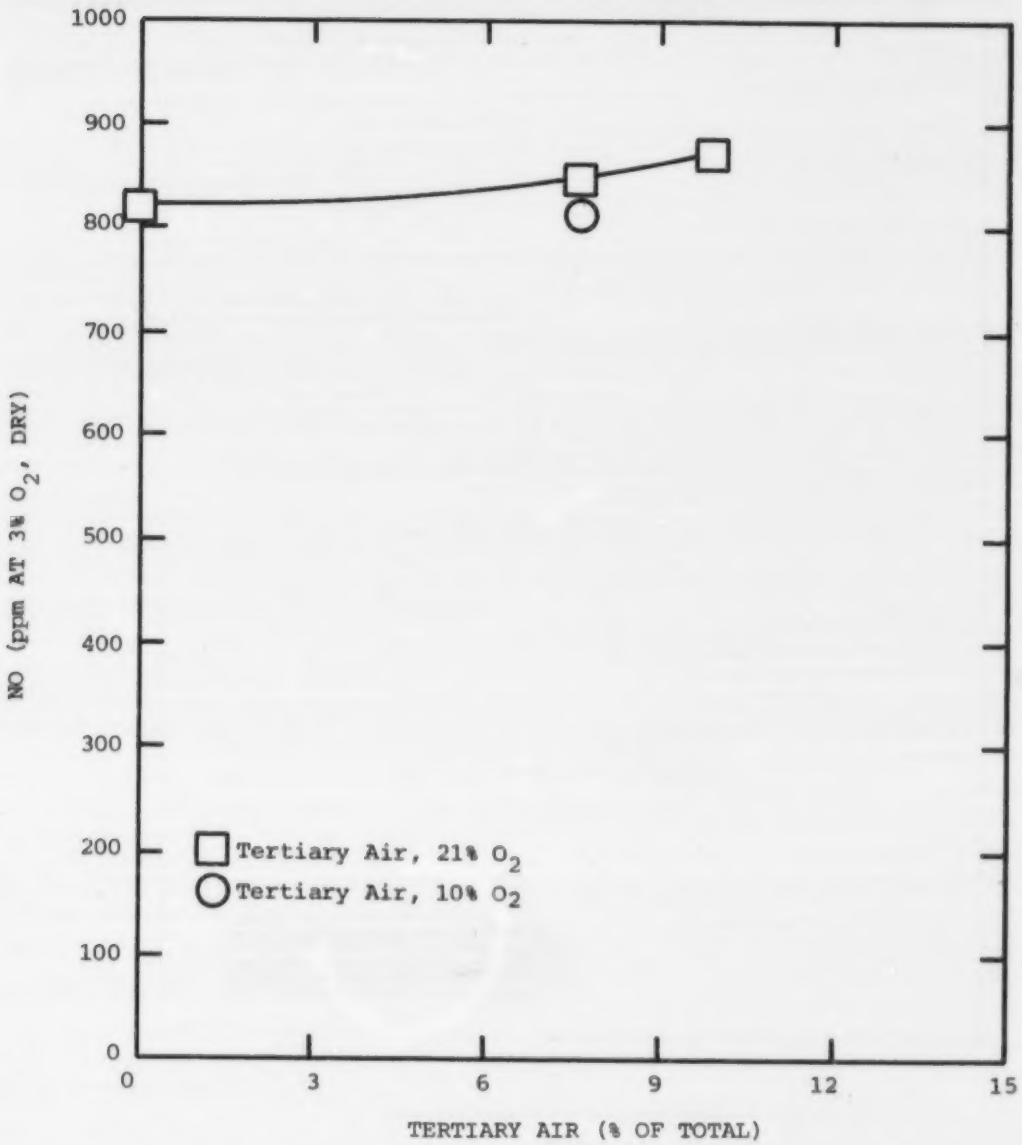


Figure 3-13. The Effect of Tertiary Air on NO Emissions

higher intensity flame. Vitiated tertiary air (tertiary air diluted with nitrogen gas) decreased NO emissions to levels comparable with the baseline condition (no tertiary air).

3.2.6 Flue Gas Recirculation

Flue gas recirculation (FGR) as a combustion modification was evaluated with the kiln firing bituminous coal. The flue gas recirculation system was described in Section 2.2 and had been checked out while the kiln was firing natural gas. Parametric tests were conducted at different recirculation rates. The results of these tests are shown in Figure 3-14 for the kiln exit O_2 of 5.4 percent and a secondary combustion air temperature of 889 K (1140°F). The effect of FGR in the secondary air on NO emissions is not as significant as that with natural gas firing. An overall reduction of only 5.4 percent was measured with a recirculation rate of approximately 21 percent.

3.2.7 Diluted Primary Air

During laboratory tests at KVB, the effect of carrier air oxygen content on NO emissions was found to be quite significant. One of the major objectives of this test program was to determine the effect of carrier air oxygen content on NO emissions under real process conditions. The carrier air (primary air) circuit of the test facility was plumbed so that an inert gas could be injected into the air stream upstream of the orifice which measured the flow in the circuit. Downstream of the measurement orifice, a sample port was installed for measuring the oxygen content of the carrier air. A portable oxygen analyzer was used for measuring the O_2 content just prior to entering the burner.

The effect of dilution of tne carrier air with an inert gas is shown in Figure 3-15 for a kiln operating oxygen level of 4.0 percent. These data show that the NO emissions are strongly influenced by the carrier air oxygen content. These data corroborate the findings and conclusions of the kiln laboratory study (Reference 1).

Figure 3-15 shows the effect of carrier gas oxygen content on NO emission rate for the subscale kiln firing bituminous coal. These data show

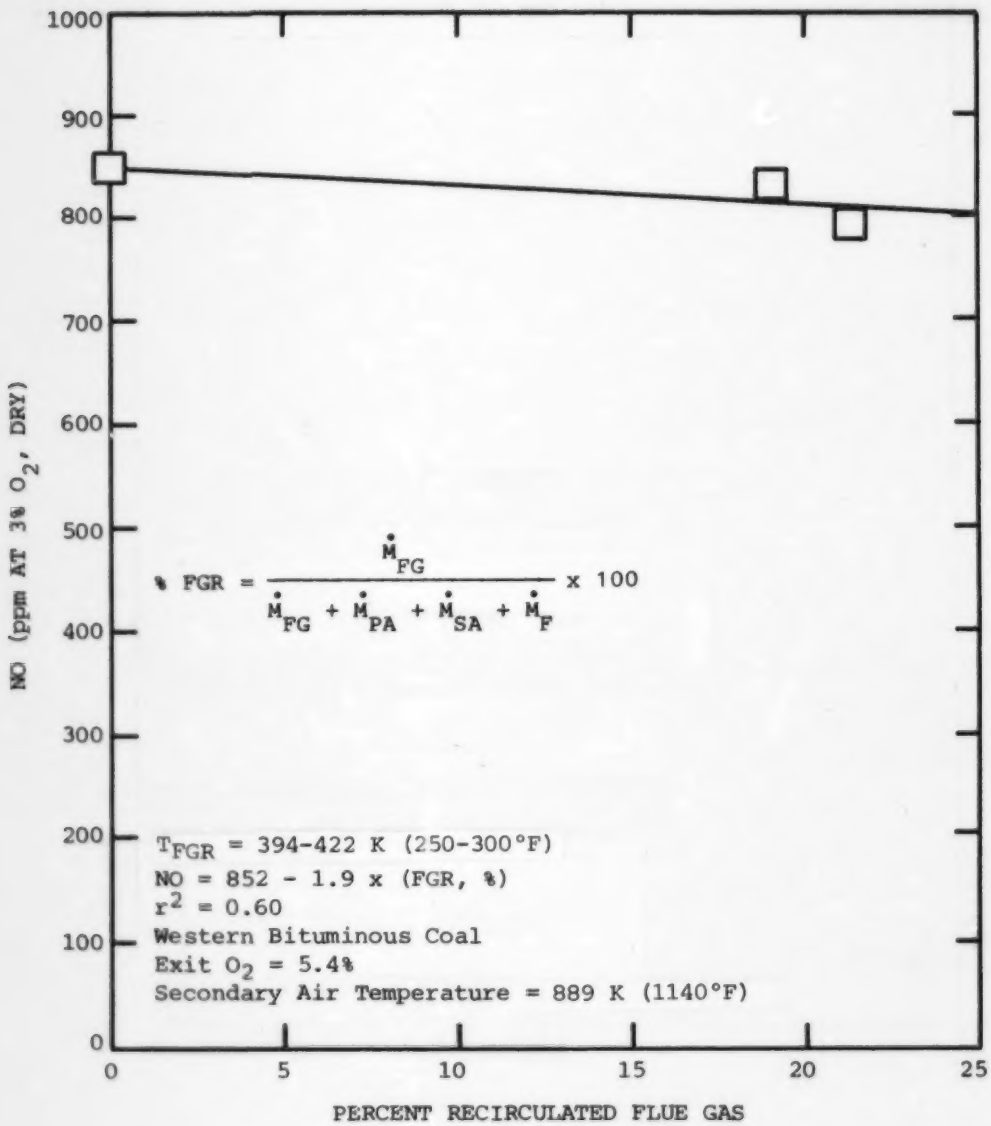


Figure 3-14. The Effect of Flue Gas Recirculation Rate on NO Emissions for a Subscale Cement Kiln

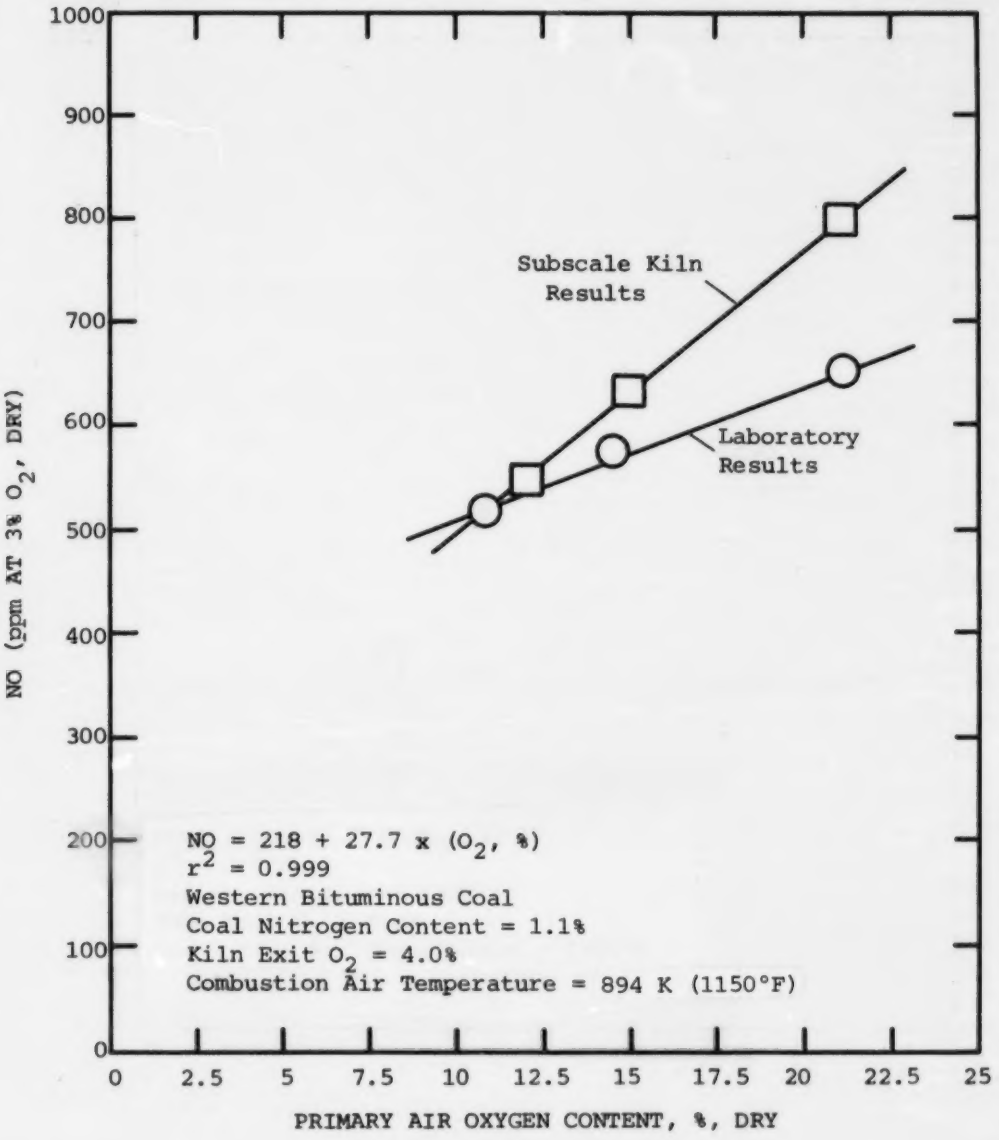


Figure 3-15. The Effect of Primary Air Oxygen Content on NO Emissions

that a reduction in NO of approximately 37 percent is possible by lowering the carrier gas oxygen to 12.5 percent. This curve shows a greater effect on NO emissions by carrier O_2 than did the laboratory data probably because the combustion air temperature was 894 K (1150°F) compared with 700 K (800°F) for the laboratory tests. A linear regression analysis of the data showed a good correlation, with a coefficient of determination, r^2, of 0.999. The regression curve for the effect of vitiated primary air on NO emission level is:

$$NO\ (ppm) = 218 + 27.7 \times (O_2,\ \%)$$

SECTION 4.0

REFERENCES

1. Tidona, R. J. et al., "Evaluation of Combustion Variable Effects on NO_x Emissions from Mineral Kilns," EPA 600/7-83-045, NTIS Order No. PB83-259655, August, 1983.

2. State of California Air Resources Board, "Suggested Control Measure for the Control of Emissions of Oxides of Nitrogen from Cement Kilns," September, 1981.

3. Peray, K. E. and Waddell, J. J., The Rotary Cement Kiln, Chemical Publishing Co., Inc., New York, 1972.

SECTION 5.0

CONVERSION FACTORS

SI Units to Metric or English Units

To Obtain	From	Multiply By
g/Mcal	ng/J	0.004186
10^6 Btu	GJ	0.948
Btu	gm cal	3.9685×10^{-3}
lb/10^6 Btu	ng/J	0.00233
ft	m	3.281
in.	cm	0.3937
ft^2	m^2	10.764
ft^3	m^3	35.314
lb	kg	2.205
Fahrenheit	Celsius	$t_F = 9/5(t_c) + 32$
Fahrenheit	Kelvin	$t_F = 1.8t_K - 460$
psig	Pa	$P_{psig} = (P_{pa})(1.450 \times 10^{-4}) - 14.7$
psia	Pa	$P_{psia} = (P_{pa})(1.450 \times 10^{-4})$
iwg (39.2°F)	Pa	$P_{iwg} = (P_{pa})(4.014 \times 10^{-3})$
10^6 Btu/hr	MW	3.413
GJ/hr	MW	3.60

To obtain ppm at 3% O_2 of	Multiply* Concentration in ng/J by
Natural Gas Fuel	
CO	3.23
HC	5.65
NO or NO_x	1.96
SO_2 or SO_x	1.41
Oil Fuel	
CO	2.93
HC	5.13
NO or NO_x	1.78
SO_2 or SO_x	1.28
Coal Fuel	
CO	2.69
HC	4.69
NO or NO_x	1.64
SO_2 or SO_x	1.18

*These conversions depend on fuel composition. The values given are for typical fuels.

APPENDIX A

KILN FEED

	Sample 1		Sample 2	
	Raw Basis (As Received)	Clinker Basis	Raw Basis (As Received)	Clinker Basis
SiO_2	13.88	22.99	14.39	22.50
Al_2O_3	2.44	4.51	2.42	3.78
Fe_2O_3	1.70	2.84	1.68	2.62
CaO	43.51	65.07	43.96	68.75
MgO	1.43	3.16	1.53	2.40
Loss	36.45	0.59	35.49	--
Na_2O	0.10	0.11	0.08	--
K_2O	0.43	0.53	0.46	--
C_3A	5.64	7.16	--	5.59
C_3S	83.05	55.19	--	79.76

APPENDIX B

COAL FUEL ANALYSIS

Sample Taken 8-4-82

Proximate Analysis	As Rec'd	Dry Basis
% Moisture	7.34	XXXXX
% Ash	11.73	12.66
% Volatile	34.95	37.72
% Fixed Carbon	45.98	49.62
	100.00	100.00
Btu/lb	10740	11591
% Sulfur	0.49	0.53

Ultimate Analysis	As Rec'd	Dry Basis
% Moisture	7.34	XXXXX
% Carbon	62.35	67.29
% Hydrogen	4.14	4.47
% Nitrogen	1.11	1.20
% Chlorine	0.04	0.04
% Sulfur	0.49	0.53
% Ash	11.73	12.66
% Oxygen (diff)	12.80	13.81
	100.00	100.00

APPENDIX C

RESIDENCE TIME IN KILN

$$T = \frac{11.4 \times L}{NDS}$$

where

T = travel time, minutes

L = length of kiln, ft

N = speed of kiln, rev. per hour

D = internal diameter, feet

S = slope of kiln, feet per foot

$$T = \frac{11.4 \times 27}{120 \times 1.25 \times 0.03}$$

$$T = \underline{68 \text{ min}}$$

APPENDIX D

CALCULATION FOR COAL FIRING BASELINE EMISSION RATE

The following emission rate equation* is used to convert uncorrected volume parts per million of NO_x to pounds of NO_x per ton of clinker produced at standard conditions of 68°F and 29 inches of mercury.

$$\frac{(ppm_v\ NO_x)(46\ gram/mole)(1.56 \times 10^{-7})(SDCFM)}{(Ton/hour\ of\ Clinker)} = \frac{lbs\ NO_x}{Ton\ of\ Clinker}$$

NO_x is expressed as NO_2.

To solve the equation, the following factors must be measured or calculated:

a. ($ppm_v\ NO_x$) is NO concentration in parts per million by volume as measured. (Only NO was measured in this test program.)

b. (SDCFM) is the volumetric stack gas flow rate corrected to standard conditions, expressed in cubic feet per minute.

c. Ton/hour clinker is calculated with calibrated raw feed conveyor system setting and the raw feed ignition loss.

The calculations and measurements for these factors are summarized below:

a. NO = 770 ppmv corrected to 3% O_2 (uncorrected % O_2 = 5.7).

   (ppmv NO) = 655 ppmv at 5.7% O_2 (after adjustments made with main flue gas damper)

b. To calculate volumetric stack flow rate while burning coal (prior to flue gas damper adjustment), the following measurements are needed to determine coal flow rate (lb/hr). A switch from gas firing to coal firing is made without altering the air flows or main flue gas damper.

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*State of California Air Resources Board, "Suggested Control Measure for the Control of Emissions of Oxides of Nitrogen from Cement Kilns," September, 1981.

(i) Calculate $\dot{M}_{air}$ (lb/hr) for gas firing based on the gas orifice $\Delta P = 0.9$, kiln exit % $O_2 = 2$

$$\dot{M}_{air} = \underbrace{660 \text{ cfh}}_{\left(\begin{array}{c}\text{fuel vol.}\\ \text{based on orifice}\\ \text{plate \#1160}\end{array}\right)} * \underbrace{0.049 \frac{\text{lb gas}}{\text{ft}^3}}_{\left(\text{gas density}\right)} * \underbrace{15.73 \frac{\text{lb air}}{\text{lb gas}}}_{\left(\text{stoichiometric } \frac{\text{air}}{\text{fuel}}\right)}$$

$$* \underbrace{1.1}_{\left(\begin{array}{c}\text{excess air}\\ \text{factor}\end{array}\right)} = 524 \text{ lb/hr}$$

(ii) Calculate $\dot{M}_{coal}$ (lb/hr) knowing stoichiometric air/fuel ratio for coal firing.

The stoichiometric air/fuel ratio is calculated from the ultimate analysis for the coal sample (Appendix B).

$$\frac{\dot{M}_a}{\dot{M}_c} = 137.28 \left[\frac{\alpha - \beta\ YO_2}{1 - 4.76\ YO_2}\right]$$

where

x = weight fractions of elements used

$$\alpha = \frac{x_C}{12} + \frac{x_H}{4} + \frac{x_S}{32} - \frac{x_O}{32}$$

$$\beta = \frac{X_H}{4} - \frac{X_N}{28} - \frac{X_O}{32}$$

$$YO_2 = 0 \text{ (stoichiometric air/fuel ratio)}$$

$$\frac{\dot{M}_a}{\dot{M}_c} = 8.66$$

$$\dot{M}_{coal} = \frac{524 \frac{lb_a}{hr}}{(1.1)(8.66 \frac{lb\ air}{lb\ fuel})}$$

$$\dot{M}_{coal} = 55 \frac{lb\ coal}{hr} \text{ (stoichiometric conditions)}$$

(iii) The volumetric dry stack gas flow rate is calculated from the following equations. For the fuel alone (based on Fuel Analysis, Appendix B) the stoichiometric flue gas flow is

$$\frac{SDCF}{lb\ coal} = 1.53\ (\%\ C) + 3.64\ (\%\ H) + 0.57\ (\%\ S) + 0.14\ (\%\ N) - 0.46\ (\%\ O_2)$$

$$= 1.53\ (62.35) + 3.64\ (4.14) + 0.57\ (0.49) + 0.14\ (1.11) - 0.46\ (12.80$$

$$= 105 \text{ SDCF/lb coal}$$

$$SDCFM_{fuel} = 55 \frac{lb\ coal}{hr} * 105 \frac{SDCF}{lb\ coal} * \frac{1\ hr}{60\ min} = 96.3 \text{ SDCFM}$$

For CO_2 evolved from the feed:

$$SDCFM_{CO_2} = 8.79 \frac{SDCF}{lb\ CO_2} * 0.3548 \frac{lb\ CO_2}{lb\ feed} * 250 \frac{lb\ feed}{hr} * \frac{1\ hr}{60\ min}$$

$$= 13 \text{ SDCFM}$$

For excess air at 5.7% O_2 dry:

$$SDCFM_{fuel} = 105 \times \frac{20.9}{20.9 - 5.7} = 144.4 \text{ SDCFM}$$

Total stack dry gas flow:

(SDCFM) = 144.4 + 13 = 157 SDCFM

c. Ton/hr clinker calculated

$$250 \frac{\text{lb feed}}{\text{hr}} \times 0.6452 \frac{\text{lb clinker}}{\text{lb feed}} \times \frac{1 \text{ ton}}{2000 \text{ lb}} = 0.081 \frac{\text{tons clinker}}{\text{hr}}$$

d. Use emission rate ($\frac{\text{lb } NO_x}{\text{ton clinker}}$) equation knowing (a), (b), and (c)

$$\frac{(655)(46)(1.56 \times 10^{-7})(157)}{0.081} = \frac{9.1 \text{ lb } NO_x}{\text{ton clinker}}$$